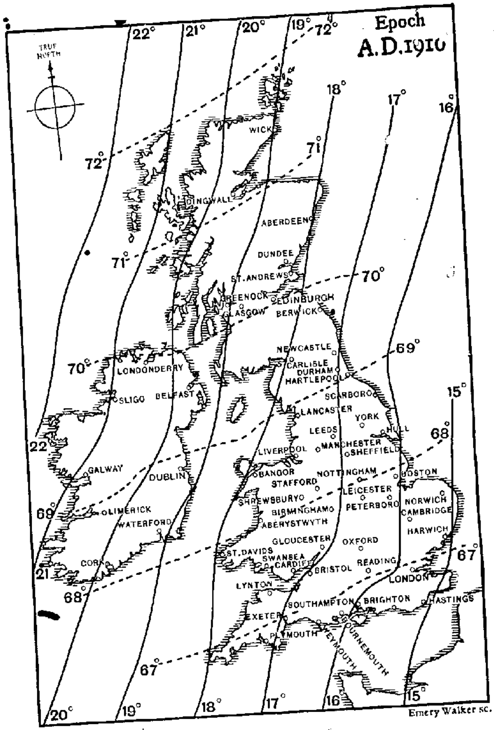

MAGNETIC CHART OF THE BRITISH ISLANDS,

ELEMENTARY LESSONS

IN

ELECTRICITY & MAGNETI

BY

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MACMILLAN AND CO., LIMITED
ST. MARTIN'S STREET, LONDON

First Edition printed 1881
Reprinted with corrections and additions April 1882
With alterations and additions November 1882
Cancel inserted November 1882, *with alterations and additions* 1883, 1884, 1885, 1886, 1887, 1889. *Reprinted May and December* 1890 ; *April and August* 1891 ; *January, May, and October* 1892, 1893, 1894
New Edition January 1895. *Reprinted October* 1895, 1897, 1899 1900, 1901. 1902, 1903, 1905 (*twice*) 1906, 1907, 1908 (*twice*) 1909 1910, 1911 (*twice*), 1912

PREFACE

THESE Elementary Lessons have now been largely rewritten. The considerable changes made have been necessitated not only by the progress of the science but by the piracy, covert as well as open, to which since its appearance in 1881 the book has been subjected.

In the thirteen years which have elapsed much addition has been made to our knowledge, and many points then in controversy have been settled. The system of electric units, elaborated first by the British Association and subsequently in several International Congresses, is now legalized in the chief civilized countries. New magnetic surveys—in England by Thorpe and Rücker, in the United States under Mendenhall—have enabled new magnetic charts to be prepared for the epoch 1900 A.D. The researches of Ewing, Hopkinson, and others on the magnetic properties of iron, and the general recognition of the principle of the magnetic circuit, have advanced the science of magnetism, to which also Ewing's molecular theory has given an added interest. The properties of alternate currents, of which in 1881 little was known, have been forced into study by the extension of their industrial uses in telephony and in electric lighting.

Entirely new is the use of polyphase alternate currents and rotatory magnetic fields for the electric transmission of power. Transformers have come into extensive employment for the distribution at low pressure of electric energy which has been transmitted from a generating station at high pressure. Accumulators for the storage of electric energy have become of great commercial importance. Electric lamps, large and small, illuminate in millions our cities, towns, villages, and ships. Electric currents for lighting and power are now supplied publicly on a very large scale from central stations operated by steam or water power. Supply-meters are in regular use, and measuring instruments of many forms have come into the market.

Along with these advances in practice there has been a no less striking progress in theory. The ideas of Faraday, as enlarged and developed by Clerk Maxwell, were in 1881 only beginning to be understood and appreciated outside a narrow circle. In 1894, thanks largely to the labours of Heaviside, Hertz, Lodge, Poynting, Fitzgerald, Boltzmann, Poincaré, and others, they are everywhere accepted. In 1881 Maxwell's electromagnetic theory of light—a conception not less far-reaching than the theory of the conservation of energy—was deemed of doubtful probability: it was not yet accepted by such great masters as Lord Kelvin or Von Helmholtz. Though adopted by the younger generation of British physicists, it needed the experimental researches of Hertz and of Lodge upon the propagation of electric waves to demonstrate its truth to their brethren in Germany, France, and America. Even now, after the most convincing experimental verifications of Maxwell's splendid generalization that light-waves are

really electric waves, many of the logical consequences of Maxwell's teaching are still ignored or misunderstood. It is still, to many, a hard saying that in an electric circuit the conducting wire though it guides does not carry the energy: that the energy-paths lie outside in the surrounding medium, not inside within the so-called conductor. That the guttapercha sheath, and not the copper wire within it, is the actual medium which conveys the impulse from one side of the Atlantic to the other in cable-telegraphy, is still incredible to those brought up in the older school of thought. But it is none the less a necessary consequence of the views which the inescapable logic of facts drove Maxwell and his followers to adopt.

This expansion of the science and of its practical applications has rendered more difficult than before the task of presenting with sufficient clearness, yet with necessary brevity, an elementary exposition of the leading phenomena, and of their relations to one another.

The author is under obligations to many scientific friends for data of which he has made use. He is under special obligations to his assistant, Mr. Miles Walker, for indefatigable proof-reading and revision of the Problems and Index.

LONDON, *September* 1894.

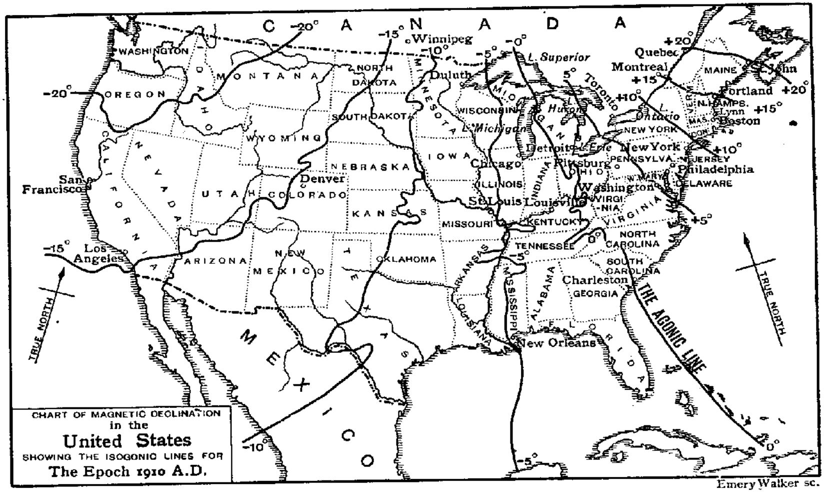

CHART OF MAGNETIC DECLINATION
in the
United States
SHOWING THE ISOGONIC LINES FOR
The Epoch 1910 A.D.

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ON

ELECTRICITY & MAGNETISM

Part First

CHAPTER I

FRICTIONAL ELECTRICITY

Lesson I.—*Electric Attraction and Repulsion*

1. Electricity.—*Electricity* is the name given to an invisible agent known to us only by the effects which it produces and by various manifestations called *electrical*. These manifestations, at first obscure and even mysterious, are now well understood, though little is yet known of the precise nature of electricity itself. It is neither matter nor energy; yet it apparently can be associated or combined with matter; and energy can be spent in moving it. Indeed its great importance to mankind arises from the circumstance that by its means energy spent in generating electric forces in one part of a system can be made to reappear as electric heat or light or work at some other part of the system; such transfer of energy taking place even to very great distances at an enormous speed. Electricity is apparently as indestructible as

matter or as energy. It can neither be created nor destroyed, but it can be transformed in its relations to matter and to energy, and it can be moved from one place to another. In many ways its behaviour resembles that of an incompressible liquid; in other ways that of a highly attenuated and weightless gas. It appears to exist distributed nearly uniformly throughout all space. Many persons (including the author) are disposed to consider it as identical with the luminiferous ether. If it be not the same thing, there is an intimate relation between the two. That this must be so, is a necessary result of the great discovery of Maxwell—the greatest scientific discovery of the nineteenth century—that light itself is an electric phenomenon, and that the light-waves are merely electric, or, as he put it, electromagnetic waves.

The name *electricity* is also given to that branch of science which deals with electric phenomena and theories. The phenomena, and the science which deals with them, fall under four heads. The manifestations of electricity when standing still are different from those of electricity moving or flowing along: hence we have to consider separately the properties of (i.) statical *charges*, and those of (ii.) *currents*. Further, electricity whirling round or in circulation possesses properties which were independently discovered under the name of (iii.) *magnetism*. Lastly, electricity when in a state of rapid vibration manifests new properties not possessed in any of the previous states, and causes the propagation of (iv.) *waves*. These four branches of the science of electricity are, however, closely connected. The object of the present work is to give the reader a general view of the main facts and their simple relations to one another.

In these first lessons we begin with charges of electricity, their production by friction, by influence, and by various other means, and shall study them mainly by the manifestations of attraction and repulsion to which they give rise. After that we go on to magnetism and

currents, and the relations between them. The subject of electric waves is briefly discussed at the end of the book.

2. Electric Attraction.—If you take a piece of sealing-wax, or of resin, or a glass rod, and rub it upon a piece of flannel or silk, it will be found to have acquired a property which it did not previously possess: namely, the power of attracting to itself such light bodies as chaff, or dust, or bits of paper (Fig. 1). This curious power

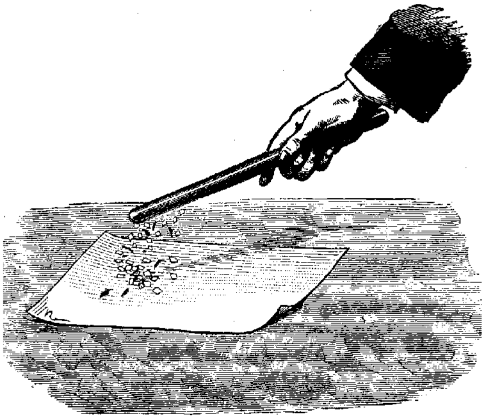


Fig. 1.

was originally discovered to be a property of **amber**, or, as the Greeks called it, ἤλεκτρον, which is mentioned by Thales of Miletus (B.C. 600), and by Theophrastus in his treatise on Gems, as attracting light bodies when rubbed. Although an enormous number of substances possess this property, amber and jet were the only two in which its existence had been recognised by the ancients, or even down to so late a date as the time of Queen Elizabeth.

About the year 1600, Dr. Gilbert of Colchester discovered by experiment that not only amber and jet, but a very large number of substances, such as diamond, sapphire, rock-crystal, glass, sulphur, sealing-wax, resin, etc., which he styled *electrics*,* possess the same property. Ever since his time the name **electricity** † has been employed to denote the agency at work in producing these phenomena. Gilbert also remarked that these experiments are spoiled by the presence of moisture.

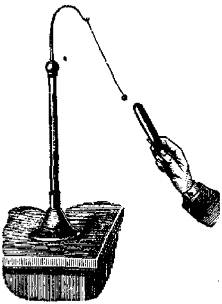


Fig. 2.

3. Further Experiments.—A better way of observing the attracting force is to employ a small ball of elder pith, or of cork, hung by a fine thread from a support, as shown in Fig. 2. A dry warm glass tube, excited by rubbing it briskly with a silk handkerchief, will attract the pith-ball strongly, showing that it is highly electrified. The most suitable rubber, if a stick of sealing-wax is used, will be found to be flannel, woollen cloth, or, best of all, fur. Boyle discovered

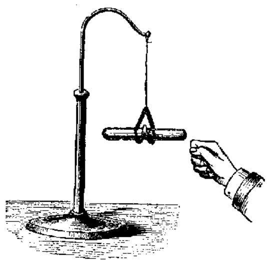


Fig. 3.

* "*Electrica;* quæ attrahunt eadem ratione ut electrum" (Gilbert).

† The first work in which this term was used is that of Robert Boyle, *On the Mechanical Production of Electricity*, published at Oxford in 1675.

that an electrified body is itself attracted by one that has not been electrified. This may be verified (see Fig. 3) by rubbing a stick of sealing-wax, or a glass rod, and hanging it in a wire loop at the end of a *silk* thread. If, then, the hand be held out towards the suspended electrified body, the latter will turn round and approach the hand. So, again, a piece of silk ribbon, if rubbed with warm indiarubber, or even if drawn between two pieces of warm flannel, and then hung up by one end, will be found to be attracted by objects presented to it. If held near the wall of the room it will fly to it and stick to it. With proper precautions it can be shown that *both* the rubber and the thing rubbed are in an electrified state, for both will attract light bodies; but to show this, care must be taken not to handle the rubber too much. Thus, if it is desired to show that when a piece of fur is rubbed upon sealing-wax, the fur becomes also electrified, it is better not to take the fur in the hand, but to cement it to the end of a glass rod as a handle. The reason of this precaution will be explained toward the close of this lesson, and more fully in Lesson IV.

A large number of substances, including iron, gold, brass, and all the metals, when held in the hand and rubbed, exhibit no sign of electrification,—that is to say, do not attract light bodies as rubbed amber and rubbed glass do. Gilbert mentions also pearls, marble, agate, and the lodestone, as substances not excited electrically by rubbing them. Such bodies were, on that account, formerly termed *non-electrics;* but the term is erroneous, for if they are mounted on glass handles and then rubbed with silk or fur, they behave as electrics.

4. Electric Repulsion.—When experimenting, as in Fig. 1, with a rubbed glass rod and bits of chopped paper, or straw, or bran, it will be noticed that these little bits are first attracted and fly up towards the excited rod, but that, having touched it, they are speedily repelled

and fly back to the table. To show this repulsion better, let a small piece of feather or down be hung by a silk thread to a support, and let an electrified glass rod be held near it. It will dart towards the rod and stick to it, and a moment later will dart away from it, repelled by an invisible force (Fig. 4), nor will it again dart towards the rod. If the experiment be repeated with another feather, and a stick of sealing-wax rubbed on flannel, the same effects will occur. But, if now the hand be held towards the feather, it will rush toward the hand, as the rubbed body (in Fig. 3) did. This proves that the feather, though it has not itself been rubbed, possesses the property originally imparted to the rod by rubbing it. In fact, it has become electrified, by having touched an electrified body which has given part of its electricity to it. It would appear then that two bodies electrified with the same electrification repel one another. This may be confirmed by a further experiment. A rubbed glass rod, hung up as in Fig. 3, is repelled by a

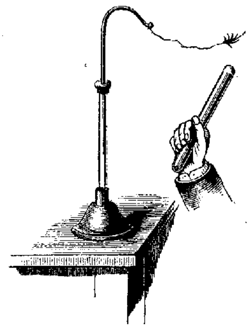


Fig. 4.

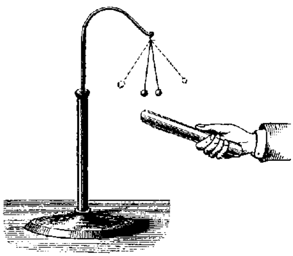


Fig. 5.

similar rubbed glass rod; while a rubbed stick of sealing-wax is repelled by a second rubbed stick of sealing-wax. Another way of showing the repulsion between two similarly electrified bodies is to hang a couple of small pith-balls, by thin linen threads, to a glass support, as in Fig. 5, and then touch them both with a rubbed glass rod. They repel one another and fly apart, instead of hanging down side by side, while the near presence of the glass rod will make them open out still wider, for now it repels them both. The self-repulsion of the parts of an electrified body is beautifully illustrated by the experiment of electrifying a soap-bubble, which *expands* when electrified.

5. Two Kinds of Electrification.—Electrified bodies do not, however, always repel one another. The feather which (see Fig. 4) has been touched by a rubbed glass rod, and which in consequence is repelled from the rubbed glass, will be *attracted* if a stick of rubbed sealing-wax be presented to it; and conversely, if the feather has been first electrified by touching it with the rubbed sealing-wax, it will be attracted to a rubbed glass rod, though repelled by the rubbed wax. So, again, a rubbed glass rod suspended as in Fig. 3 will be attracted by a rubbed piece of sealing-wax, or resin, or amber, though repelled by a rubbed piece of glass. The two pith-balls touched (as in Fig. 5) with a rubbed glass rod fly from one another by repulsion, and, as we have seen, fly wider asunder when the excited glass rod is held near them; yet they fall nearer together when a rubbed piece of sealing-wax is held under them, being attracted by it. Symmer first observed such phenomena as these, and they were independently discovered by Du Fay, who suggested in explanation of them that there were two different kinds of electricity which attracted one another, while each repelled itself. The electricity produced on glass by rubbing it with silk he called *vitreous* electricity, supposing, though erroneously, that glass could yield no

other kind ; and the electricity excited in such substances as sealing-wax, resin, shellac, indiarubber, and amber, by rubbing them on wool or flannel, he termed *resinous* electricity. The kind of electricity produced is, however, found to depend not only on the thing rubbed but on the rubber also ; for glass yields "resinous" electricity when rubbed with a cat's skin, and resin yields "vitreous" electricity if rubbed with a soft amalgam of tin and mercury spread on leather. Hence these names have been abandoned in favour of the more appropriate terms introduced by Franklin, who called the electricity excited upon glass by rubbing it with silk, *positive* electricity, and that produced on resinous bodies by friction with wool or fur, *negative* electricity. The observations of Symmer and Du Fay may therefore be stated as follows:—Two positively electrified bodies apparently repel one another: two negatively electrified bodies apparently repel one another: but a positively electrified body and a negatively electrified body apparently attract one another. It is now known that these effects which appear like a repulsion and an attraction between bodies at a distance from one another, are really due to actions going on *in the medium* between them. The positive charge does not really attract the negative charge that is near it; but both are urged toward one another by stresses in the medium in the intervening space.

6. Simultaneous Production of both Electrical States.—Neither kind of electrification is produced alone; there is always an equal quantity of both kinds produced; one kind appearing on the thing rubbed and an equal amount of the other kind on the rubber. The clearest proof that these amounts are *equal* can be given in some cases. For it is found that if both the − electricity of the rubber and the + electricity of the thing rubbed be imparted to a third body, that third body will show *no electrification at all*, the two equal and opposite electrifications having exactly neutralized each other. A simple

experiment consists in rubbing together a disk of sealing-wax and one covered with flannel, both being held by insulating handles. To test them is required an insulated pot and an electroscope, as in Fig. 29. If either disk be inserted in the pot the leaves of the electroscope will diverge; but if both are inserted at the same time the leaves do not diverge, showing that the two charges on the disks are equal and of opposite sign.

In the following list the bodies are arranged in such an order that if any two be rubbed together the one which stands earlier in the series becomes positively electrified, and the one that stands later negatively electrified :—*Fur, wool, ivory, glass, silk, metals, sulphur, indiarubber, guttapercha, collodion,* or *celluloid.*

7. Theories of Electricity.—Several theories have been advanced to account for these phenomena, but all are more or less unsatisfactory. Symmer proposed a **"two-fluid" theory,** according to which there are two imponderable electric fluids of opposite kinds, which neutralize one another when they combine, and which exist combined in equal quantities in all bodies until their condition is disturbed by friction. A modification of this theory was made by Franklin, who proposed instead a **"one-fluid" theory,** according to which there is a single electric fluid distributed usually uniformly in all bodies, but which, when they are subjected to friction, distributes itself unequally between the rubber and the thing rubbed, one having more of the fluid, the other less, than the average. Hence the terms *positive* and *negative,* which are still retained; that body which is supposed to have an excess being said to be charged with positive electricity (usually denoted by the *plus* sign +), while that which is supposed to have less is said to be charged with negative electricity (and is denoted by the *minus* sign −). These terms are, however, purely arbitrary, for in the present state of science we do not know which of these two states really means more and

which means less. In many ways electricity behaves as a weightless substance as incompressible as any material liquid. It is, however, quite certain that *electricity is not a material fluid*, whatever else it may be. For while it resembles a fluid in its property of apparently flowing from one point to another, it differs from every known fluid in almost every other respect. It possesses no weight; it repels itself. It is, moreover, quite impossible to conceive of two fluids whose properties should in every respect be the precise opposites of one another. For these reasons it is clearly misleading to speak of an electric fluid or fluids, however convenient the term may seem to be. In metals and other good conductors electricity can apparently move and flow quite easily in *currents.* In transparent solids such as glass and resin, and in many transparent liquids such as oils, and in gases such as the air (if still, and not rarefied), electricity apparently cannot flow. Even a vacuum appears to be a non-conductor. In the case of all non-conductors electricity can only be moved by an action known as *displacement* (see Art. 57).

It appears then that in metals electricity can easily pass from molecule to molecule; but in the case of non-conductors the electricity is in some way stuck to the molecules, or associated with them. Some electricians, notably Faraday, have propounded a **molecular theory** of electricity, according to which the electrical states are the result of certain peculiar conditions of the molecules of the surfaces that have been rubbed. Another view is to regard the state of electrification as related to the *ether* (the highly-attenuated medium which fills all space, and is the vehicle by which light is transmitted), which is known to be associated with the molecules of matter. Some indeed hold that the ether itself is electricity; and that the two states of positive and negative electrification are simply due to displacement of the ether at the surfaces of bodies. In these lessons we shall avoid as

far as possible all theories, and shall be content to use the term **electricity**.

8. **Charge.**—The quantity of electrification of either kind produced by friction or other means upon the surface of a body is spoken of as a **charge**, and a body when electrified is said to be *charged*. It is clear that there may be charges of different values as well as of either kind. When the charge of electricity is removed from a charged body it is said to be *discharged*. Good conductors of electricity are instantaneously discharged if touched by the hand or by any conductor in contact with the ground, the charge thus finding a means of escaping to earth or to surrounding walls. A body that is not a good conductor may be readily discharged by passing it rapidly through the flame of a spirit-lamp or a candle; for the hot gases instantly carry off the charge and dissipate it in the air.

Electricity may either reside upon the surface of bodies as a *charge*, or flow through their substance as a *current*. That branch of the science which treats of the laws of the charges, that is to say, of electricity at rest, upon the surface of bodies is termed **electrostatics**, and is dealt with in Chapter IV. The branch of the subject which treats of the flow of electricity in currents is dealt with in Chapter III., and other later portions of this book.

9. **Modes of representing Electrification.**—Several modes are used to represent the electrification of surfaces. In Figs. 6, 7, and 8 are represented two disks, —A covered with woollen cloth, B of some resinous body, — which have been rubbed together so that A has become positively, B negatively electrified. In Fig. 6 the surfaces are marked with *plus* (+) and *minus* (−) signs. In Fig. 7 dotted lines are drawn just outside

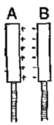


Fig. 6.

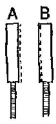


Fig. 7.

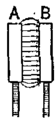


Fig. 8.

the positively electrified surface and just within the negatively electrified surface, as though one had a surplus and the other a deficit of electricity. In Fig. 8 lines are drawn across the intervening space from the positively electrified surface to the opposite negative charge. The advantages of this last mode are explained in Art. 13.

10. Conductors and Insulators.—The term "conductors," used above, is applied to those bodies which readily allow electricity to flow through them. Roughly speaking, bodies may be divided into two classes—those which conduct and those which do not; though very many substances are partial conductors, and cannot well be classed in either category. All the metals conduct well; the human body conducts, and so does water. On the other hand glass, sealing-wax, silk, shellac, gutta-percha, indiarubber, resin, fatty substances generally, and the air, are **non-conductors.** On this account these substances are used to make supports and handles for electrical apparatus where it is important that the electricity should not leak away; hence they are sometimes called **insulators** or *isolators*. Faraday termed them **dielectrics.** We have remarked above that the name of *non-electrics* was given to those substances which, like the metals, yield no sign of electrification when held in the hand and rubbed. We now know the reason why they show no electrification; for, being good conductors, the electrification flows away as fast as it is generated. The observation of Gilbert that electrical experiments fail in damp weather is also explained by the knowledge that water is a conductor, the film of moisture on the surface of damp bodies causing the electricity produced by friction to leak away as fast as it is generated.

11. Other Electrical Effects.—The production of electricity by friction is attested by other effects than those of attraction and repulsion, which hitherto we have assumed to be the test of the presence of electricity. Otto von Guericke first observed that sparks and flashes

of light could be obtained from highly electrified bodies at the moment when they were discharged. Such sparks are usually accompanied by a snapping sound, suggesting on a small scale the thunder accompanying the lightning spark, as was remarked by Newton and other early observers. Pale flashes of light are also produced by the discharge of electricity through tubes partially exhausted of air by the air-pump. Other effects will be noticed in due course.

12. Other Sources of Electrification. — The student must be reminded that *friction* is by no means the only source of electrification. The other sources, percussion, compression, heat, chemical action, physiological action, contact of metals, etc., will be treated of in Lesson VII. We will simply remark here that friction between two different substances *always* produces electrical separation, no matter what the substances may be. Symmer observed the production of electrification when a silk stocking was drawn over a woollen one, though woollen rubbed upon woollen, or silk rubbed upon silk, produces no electrical effect. If, however, a piece of rough glass be rubbed on a piece of smooth glass, electrification is observed; and indeed the conditions of the surface play a very important part in the production of electrification by friction. In general, of two bodies thus rubbed together, that one becomes negatively electrical whose particles are the more easily removed by friction. Differences of temperature also affect the electrical conditions of bodies, a warm body being usually negative when rubbed on a cold piece of the same substance. The quantity of electrification produced is, however, not proportional to the amount of the actual mechanical friction; hence it appears doubtful whether friction is truly the cause of the electrification. Something certainly happens when the surfaces of two different substances are brought into intimate contact, which has the result that when they are drawn apart they are found (provided at least one of

them is a non-conductor) to have acquired opposite charges of electrification; one surface having apparently taken some electricity from the other. But these opposite charges attract one another and cannot be drawn apart without there being mechanical work done upon the system. The work thus spent is stored up in the act of separating the charged surfaces; and as long as the charges remain separated they constitute a store of potential energy. The so-called frictional electric machines are therefore machines for bringing dissimilar substances into intimate contact, and then drawing apart the particles that have touched one another and become electrical.

If the two bodies that are rubbed together are both good conductors, they will not become strongly electrified, even if held on insulating handles. It is quite likely, however, that the heat produced by friction, as in the bearings of machinery, is due to electric currents generated where the surfaces meet and slip.

13. Electric Field. — Whenever two oppositely charged surfaces are placed near one another they tend to move together, and the space between them is found to be thrown into a peculiar state of stress, as though the medium in between had been stretched. To explore the space between two bodies one of which has been positively and the other negatively electrified, we may use a light pointer (Fig. 9) made of a small piece of very thin paper pierced with a hole through which passes a long thread of glass. It will be found that this pointer tends to point across from the positively electrified surface to the negatively electrified surface, along invisible *lines of electric force*. The space so filled with electric lines of force is called an *electric field*. In Fig. 8 A and B represent two bodies the surfaces of which have been electrified, the one positively, the other negatively. In

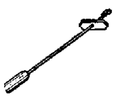


Fig. 9.

the field between them the electric lines pass across almost straight, except near the edges, where they are curved. Electric lines of force start from a positively charged surface at one end, and end on a negatively charged surface at the other end. They never meet or cross one another. Their direction indicates that of the resultant electric force at every point through which they pass. The stress in the medium thus mapped out by the lines of force acts as a tension along them, as though they tended to shorten themselves.

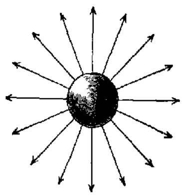


Fig. 10.

In fact in Fig. 8 the tension in the medium draws the two surfaces together. There is also a pressure in the medium at right angles to the lines, tending to widen the distance between them. Fig. 10 represents a ball which has been positively electrified, and placed at a distance from other objects; the lines in the field being simply radial.

LESSON II.—*Electroscopes*

14. Simple Electroscopes.—An instrument for detecting whether a body is electrified or not, and whether the electrification is positive or negative, is termed an **Electroscope.** The feather which was attracted or repelled, and the two pith-balls which flew apart, as we found in Lesson I., are in reality simple electroscopes. There are, however, a number of pieces of apparatus better adapted for this particular purpose, some of which we will describe.

15. Needle Electroscope.—The earliest electroscope was that devised by Dr. Gilbert, and shown in Fig. 11, which consists of a stiff strip balanced lightly upon a sharp point. A thin strip of brass or wood, a straw, or

even a goose quill, balanced upon a sewing needle, will serve equally well. When an electrified body is held near

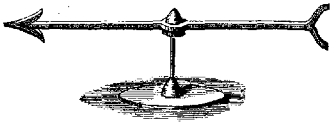


Fig. 11.

the electroscope it is attracted and turned round, and will thus indicate the presence of electric charges far too feeble to attract bits of paper from a table.

16. Gold-Leaf Electroscope.—A still more sensi-

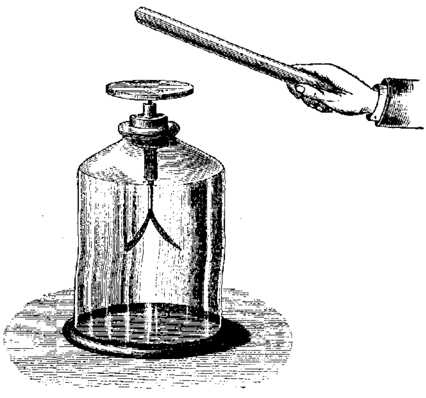


Fig. 12.

tive instrument is the **Gold-Leaf Electroscope** invented by Bennet, and shown in Fig. 12. We have seen how two pith-balls when similarly electrified repel

one another and stand apart, gravity being partly overcome by the force of the electric repulsion. A couple of narrow strips of the thinnest tissue paper, hung upon a support, will behave similarly when electrified. But the best results are obtained with two strips of gold-leaf, which, being excessively thin, is much lighter than the thinnest paper. The Gold-Leaf Electroscope is conveniently made by suspending the two leaves within a wide-mouthed glass jar, which both serves to protect them from draughts of air and to support them from contact with the ground. The mouth of the jar should be closed by a plug of paraffin wax, through which is pushed a bit of varnished glass tube. Through this passes a stiff brass wire, the lower end of which is bent at a right angle to receive the two strips of gold-leaf, while the upper supports a flat plate of metal, or may be furnished with a brass knob. When kept dry and free from dust it will indicate excessively small quantities of electrification. A rubbed glass rod, even while two or three feet from the instrument, will cause the leaves to repel one another. The chips produced by sharpening a pencil, falling on the electroscope top, are seen to be electrified. If the knob be even brushed with a small camel's-hair brush, the slight friction produces a perceptible effect. With this instrument all kinds of friction can be shown to produce electrification. Let a person, *standing upon an insulating support*,—such as a stool with glass legs, or a board supported on four glass tumblers,—be briskly struck with a silk handkerchief, or with a fox's tail, or even brushed with a clothes' brush, he will be electrified, as will be indicated by the electroscope if he place one hand on the knob at the top of it. The Gold-Leaf Electroscope can further be used to indicate the *kind* of electrification on an excited body. Thus, suppose we rubbed a piece of brown paper with a piece of indiarubber and desired to find out whether the electrification excited on the paper was + or –, we should

proceed as follows :—First charge the gold leaves of the electroscope by touching the knob with a glass rod rubbed on silk. The leaves diverge, being electrified with + electrification. When they are thus charged the approach of a body which is positively electrified will cause them to diverge still more widely ; while, on the approach of one negatively electrified, they will tend to close together. If now the brown paper be brought near the electroscope, the leaves will be seen to diverge more, proving the electrification of the paper to be of the same kind as that with which the electroscope is charged, or positive.

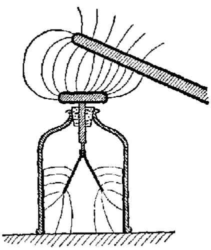


Fig. 13.

Sometimes the outer surface of the glass jar containing the gold leaves is covered with wire gauze or strips of foil to shield the leaves from the influence of external bodies. A preferable way is to use glass of a kind that conducts.

The part played by the surrounding medium in the operation of the electroscope is illustrated by Fig. 13. Of the electric lines in the field surrounding the rubbed rod a number will pass into the metal cap of the electroscope and emerge below, through the leaves. The nearer the rod is brought, the greater will be the number of electric lines thus affecting the instrument. There being a tension along the lines and a pressure across them, the effect is to draw the gold leaves apart as though they repelled each other.

The Gold-Leaf Electroscope will also indicate roughly the amount of electrification on a body placed in contact with it, for the gold leaves open out more widely when the charge thus imparted to them is greater. For exact measurement, however, of the degree of electrification,

recourse must be had to the instruments known as Electrometers, described in Lesson XXII.

In another form of electroscope (Bohnenberger's) a single gold leaf is used, and is suspended between two metallic plates, one of which can be positively, the other negatively electrified, by placing them in communication with the poles of a "dry pile" (Art. 193). If the gold leaf be charged positively or negatively it will be attracted to one side and repelled from the other, according to the law of attraction and repulsion mentioned in Art. 4.

17. Henley's Semaphore.—As an indicator for large charges of electricity there is sometimes used a semaphore like that shown in Fig. 14. It consists of a pith-ball at the end of a light arm fixed on a pivot to an upright. When the whole is electrified the pith-ball is repelled from the upright and flies out at an angle, indicated on a graduated scale or dial behind it. This little electroscope, which is seldom used except to show whether an electric machine or a Leyden battery is charged, must on no account be confused with the delicate "Quadrant Electrometer" described in Lesson XXII., whose object is to *measure* very small charges of electricity—not to *indicate* large ones.

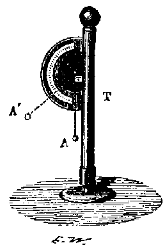


Fig. 14.

18. The Torsion Balance.—Although more properly an *Electrometer* than a mere *Electroscope*, it will be most convenient to describe here the instrument known as the Torsion Balance (Fig. 15). This instrument, once famous, but now quite obsolete, served to measure the force of the repulsion between two similarly electrified bodies, by balancing the repelling force against the force exerted by a fine wire in untwisting itself after it has been twisted. The torsion balance consists of a light arm

or lever of shellac suspended within a cylindrical glass case by means of a fine silver wire. At one end this lever is furnished with a gilt pith-ball *n*. The upper end of the silver wire is fastened to a brass top, upon which a circle, divided into degrees, is cut. This top can be turned round in the tube which supports it, and is called the torsion-head. Through an aperture in the cover there can be introduced a second gilt pith-ball *m*, fixed to the end of a vertical glass rod *a*. Round the glass case, at the level of the pith-balls, a circle is drawn, and divided also into degrees.

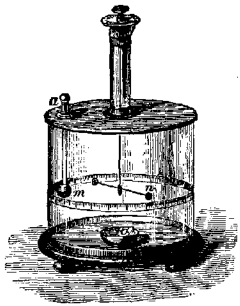


Fig. 15.

In using the torsion balance to measure the amount of a charge of electricity, the following method is adopted :—First, the torsion-head is turned round until the two pith-balls *m* and *n* just touch one another. Then the glass rod *a* is taken out, and the charge of electricity to be measured is imparted to the ball *m*, which is then replaced in the balance. As soon as *m* and *n* touch one another, part of the charge passes from *m* to *n*, and they repel one another because they are then similarly electrified. The ball *n*, therefore, is driven round and twists the wire up to a certain extent. The force of repulsion becomes less and less as *n* gets farther and farther from *m;* but the force of the twist gets greater and greater the more the wire is twisted. Hence these two forces will balance one another when the balls are separated by a certain distance, and it is clear that a large charge of electricity will repel the ball *n* with a greater force than a lesser charge would. The

distance through which the ball is repelled is read off in angular degrees of the scale. When a wire is twisted, the force with which it tends to untwist is precisely proportional to the amount of the twist. The force required to twist the wire ten degrees is just ten times as great as the force required to twist it one degree. In other words, *the* **force** *of torsion is proportional to the* **angle** *of torsion.* The angular distance between the two balls is, when they are not very widely separated, very nearly proportional to the actual straight distance between them, and represents the force exerted between electrified balls *at that distance* apart. The student must, however, carefully distinguish between the measurement of the **force** and the measurement of the actual **quantity** of electricity with which the instrument is charged. For the force exerted between the electrified balls will vary at different distances according to a particular law known as the "law of inverse squares," which requires to be carefully explained.

19. The Law of Inverse Squares.—Coulomb proved, by means of the Torsion Balance, that the force exerted between two small electrified bodies varies inversely as the square of the distance between them when the distance is varied. Thus, suppose two small electrified bodies 1 inch apart repel one another with a certain force, at a distance of 2 inches the force will be found to be only one quarter as great as the force at 1 inch; and at 10 inches it will be only $\frac{1}{100}$ part as great as at 1 inch. This law is proved by the following experiment with the torsion balance. The two scales were adjusted to 0°, and a certain charge was then imparted to the balls. The ball *n* was repelled round to a distance of 36°. The twist on the wire between its upper and lower ends was also 36°, or the force tending to repel was thirty-six times as great as the force required to twist the wire by 1°. The torsion-head was now turned round so as to twist the thread at the

LESSON III.—*Electrification by Influence*

22. Influence—We have now learned how two charged bodies may apparently attract or repel one another. It is sometimes said that it is the charges in the bodies which attract or repel one another; but as electrification is not known to exist except in or on material bodies, the proof that it is the charges themselves which are acted upon is only indirect. Nevertheless there are certain matters which support this view, one of these

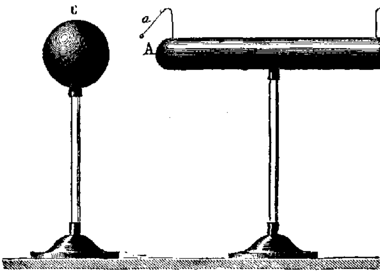


Fig. 17.

being the electric influence exerted by an electrified body upon one not electrified.

Suppose we electrify positively a ball C, shown in Fig. 17, and hold it near to a body that has not been electrified, what will occur? We take for this experiment the apparatus shown on the right, consisting of a long sausage-shaped piece of metal, either hollow or solid, held upon a glass support. This "conductor," so called because it is made of metal which permits electricity to pass freely through it or over its surface, is supported on glass to

prevent the escape of electricity to the earth, glass being a non-conductor. The influence of the positive charge of the ball placed near this conductor is found to *induce* electrification on the conductor, which, although it has not been rubbed itself, will be found to behave at its two ends as an electrified body. The ends of the conductor will attract little bits of paper; and if pith-balls be hung to the ends they are found to be repelled. It will, however, be found that the middle region of the long-shaped conductor will give no sign of any electrification. Further examination will show that the two electrifications on the ends of the conductor are of opposite kinds, that nearest the excited glass ball being a negative charge, and that at the farthest end being an equal charge, but of positive sign. It appears then that a positive charge attracts negative and repels positive, and that this influence can be exerted at a distance from a body. If we had begun with a charge of negative electrification upon a stick of sealing-wax, the presence of the negative charge near the conductor would have induced a positive charge on the near end, and negative on the far end. This action, discovered in 1753 by John Canton, is spoken of as **influence** or **electrostatic induction.*** It will take place across a considerable distance. Even if a large sheet of glass be placed between, the same effect will be produced. When the electrified body is removed both the charges disappear and leave no trace behind, and the glass ball is found to be just as much electrified as before; it has parted with none of its own charge. It

* The word *induction* originally used was intended to denote an action at a distance, as distinguished from *conduction*, which implied the conveyance of the action by a material conductor. But there were discovered other actions at a distance, namely, the induction of currents by moving magnets, or by other currents, and the induction of magnetism in iron in the presence of a neighbouring magnet. As the term *induction* has now been officially adopted for the induction of currents, its use in other senses ought to be dropped. Hence the preference now given to the term *influence* for the induction of charges by charges.

will be remembered that on one theory a body charged positively is regarded as having *more* electricity than the things round it, while one with a negative charge is regarded as having *less*. According to this view it would appear that when a body (such as the + electrified glass ball) having more electricity than things around it is placed near an insulated conductor, the uniform distribution of electricity in that conductor is disturbed, the electricity flowing away from that end which is near the + body, leaving less than usual at that end, and producing more than usual at the other end. This view of things will account for the disappearance of all signs of electrification when the electrified body is removed, for then the conductor returns to its former condition; and being neither more nor less electrified than all the objects around on the surface of the earth, will show neither positive nor negative charge.

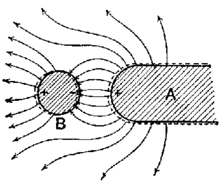


Fig. 18.

The action is not, however, a mere action at a distance; it is one in which the intervening medium takes an essential part. Consider (Fig. 18) what takes place when an insulated, non-electrified metal ball B is brought under the influence of a positively electrified body A. At once some of the electric lines of the field that surrounds A pass through B, entering it at the side nearer A, and leaving it at the farther side. As the ball B has no charge of its own, as many electric lines will enter on one side as leave on the other; or, in other words, the induced negative charge on one side and the induced positive charge on the other will be exactly equal in amount. They will not, however, be quite equally distributed, the negative charge on the side nearer A being more concentrated, and the lines in the field on that side denser.

23. Effects of Influence.—If the conductor be made in two parts, which, while under the influence of the electrified body, are separated, then on the removal of the electrified body the two charges can no longer return to neutralize one another, but remain each on its own portion of the conductor.

If the conductor be not insulated on glass supports, but placed in contact with the ground, that end only which is nearest the electrified body will be found to be electrified. The repelled charge is indeed repelled as far as possible into the walls of the room; or, if the experiment be performed in the open air, into the earth. One kind of electrification only is under these circumstances to be found, namely, the opposite kind to that of the excited body, whichever this may be. The same effect occurs in this case as if an electrified body had the power of attracting up the opposite kind of charge out of the earth.

The quantity of the two charges thus separated by influence on such a conductor in the presence of a charge of electricity, depends upon the amount of the charge, and upon the distance of the charged body from the conductor. A highly electrified glass rod will exert a greater influence than a less highly electrified one; and it produces a greater effect as it is brought nearer and nearer. The utmost it can do will be to induce on the near end a negative charge equal in amount to its own positive charge, and a similar amount of positive electrification at the far end; but usually, before the electrified body can be brought so near as to do this, something else occurs which entirely alters the condition of things. As the electrified body is brought nearer and nearer, the charges of opposite sign on the two opposed surfaces attract one another more and more strongly and accumulate more and more densely, until, as the electrified body approaches very near, a spark is seen to dart across, the two charges thus rushing together to neutralize one

another, leaving the induced charge of positive electricity, which was formerly repelled to the other end of the conductor, as a permanent charge after the electrified body has been removed.

In Fig. 19 is illustrated the operation of gradually lowering down over a table a positively electrified metal ball. The nearer it approaches the table, the more does the electric field surrounding it concentrate itself in the gap between the ball and the table top; the latter becoming negatively electrified by influence. Where the electric lines are densest the tension in the medium is greatest, until when the ball is lowered still further the mechanical resistance of the air can no longer withstand the stress; it breaks down and the layer of air is pierced by a spark. If oil is used as a surrounding medium instead of air, it will be found to stand a much greater stress without being pierced.

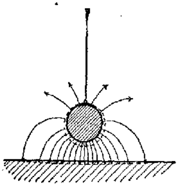


Fig. 19.

24. Attraction due to Influence.—We are now able to apply the principle of influence to explain why an electrified body should attract things that have not been electrified at all. Fig. 18, on p. 26, may be taken to represent a light metal ball B hung from a silk thread presented to the end of a rubbed glass rod A. The positive charge on A produces *by influence* a negative charge on the nearer side of B and an equal positive charge on the far side of B. The nearer half of the ball will therefore be attracted, and the farther half repelled; but the attraction will be stronger than the repulsion, because the attracted charge is nearer than the repelled. Hence on the whole the ball will be attracted. It can easily be observed that if a ball of non-conducting substance, such as wax, be employed, it is not attracted

so much as a ball of conducting material. This in itself *proves* that influence really precedes attraction.

Another way of stating the facts is as follows:—The tension along the electric field on the right of B will be greater than that on the left, because of the greater concentration of the electric lines on the right.

25. Dielectric Power.—We have pointed out several times what part the intervening medium plays in these actions at a distance. The air, oil, glass, or other material between does not act simply as a non-conductor; it takes part in the propagation of the electric forces. Hence Faraday, who discovered this fact, termed such materials *dielectrics*. Had oil, or solid sulphur, or glass, been used instead of air, the influence exerted by the presence of the electrified body at the same distance would have been greater. The power of a non-conducting substance to convey the influence of an electrified body across it is called its *dielectric power* (or was formerly called its specific *inductive capacity*, see Art. 56 and Lesson XXIII.).

26. The Electrophorus.—We are now prepared to explain the operation of a simple and ingenious instrument, devised by Volta in 1775, for the purpose of procuring, by the principle of influence, an unlimited number of charges of electricity from one single charge. This instrument * is the **Electrophorus** (Fig. 20). It consists of two parts, a round cake of resinous material cast in a metal dish or "sole," about 12 inches in diameter, and a round disk of slightly smaller diameter made of metal, or of wood covered with tinfoil, and provided with a glass handle. Shellac, or sealing-wax, or a mixture of resin, shellac, and Venice turpentine, may be used to make the cake. A slab of sulphur will also answer, but it is liable to crack. Sheets of hard ebonized indiarubber are excellent; but the surface of this substance

* Volta's electrophorus was announced in 1775. Its principle had already been anticipated by Wilcke, who in 1762 described to the Swedish Academy of Sciences two "charging-machines" working by influence.

requires occasional washing with ammonia and rubbing with paraffin oil, as the sulphur contained in it is liable to oxidize and to attract moisture. To use the electrophorus the resinous cake must be beaten or rubbed with a warm piece of woollen cloth, or, better still, with a cat's

Fig. 20.

skin. The disk or "cover" is then placed upon the cake, touched momentarily with the finger, then removed by taking it up by the glass handle, when it is found to be powerfully electrified with a positive charge, so much so indeed as to yield a spark when the knuckle is presented to it. The "cover" may be replaced, touched, and once more removed, and will thus yield any number of sparks.

the original charge on the resinous plate meanwhile remaining practically as strong as before.

The theory of the electrophorus is very simple, provided the student has clearly grasped the principle of influence explained above. When the resinous cake is first beaten with the cat's skin its surface is negatively electrified, as indicated in Fig. 21. When the metal disk is placed down upon it, it rests really only on three or four points of the surface, and may be regarded as an insulated conductor in the presence of an electrified body. The negative electrification of the cake therefore acts by influence on the metallic disk or "cover," the natural electricity in it being displaced downwards, producing a positive charge on the under side, and leaving the upper

Fig. 21.

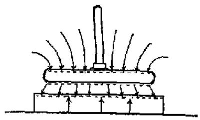


Fig. 22.

side negatively electrified. This state of things is shown in Fig. 22. If now the cover be touched for an instant with the finger, the negative charge of the upper surface will be neutralized by electricity flowing in from the earth through the hand and body of the experimenter. The attracted positive charge will, however, remain, being bound as it were by its attraction towards the negative charge on the cake. Fig. 23 shows the condition of things after the cover has been touched. If, finally, the cover be lifted by its handle, the remaining positive charge will be no longer "bound" on the lower surface by attraction, but will distribute itself on both sides of the cover, and may be used to give a spark, as already said. It is clear that no part of the original charge has been consumed in the process, which may be repeated as

often as desired. As a matter of fact, the charge on the cake slowly dissipates—especially if the air be damp. Hence it is needful sometimes to renew the original charge by afresh beating the cake with the cat's skin. The labour of touching the cover with the finger at each operation may be saved by having a pin of brass or a strip of tinfoil projecting from the metallic "sole" on to the top of the cake, so that it touches the plate each time, and thus neutralizes the negative charge by allowing electricity to flow in from the earth.

The principle of the electrophorus may then be summed up in the following sentence. *A conductor if touched*

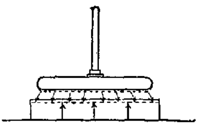


Fig. 23.

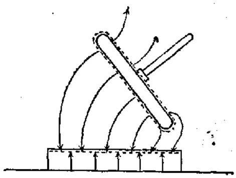


Fig. 24.

*while under the influence of a charged body acquires thereby a charge of opposite sign.**

Since the electricity thus yielded by the electrophorus is not obtained at the expense of any part of the original charge, it is a matter of some interest to inquire what the source is from which the energy of this apparently unlimited supply is drawn; for it cannot be called into

* Priestley, in 1767, stated this principle in the following language:—"The electric fluid, when there is a redundancy of it in any body, repels the electric fluid in any other body, when they are brought within the sphere of each other's *influence*, and drives it into the remote parts of the body; or quite out of the body, if there be any outlet for that purpose. In other words, bodies immerged in electric atmospheres always become possessed of the electricity, contrary to that of the body, in whose atmosphere they are immerged."

existence without the expenditure of some other form of energy, any more than a steam-engine can work without fuel. As a matter of fact it is found that it is a little harder work to lift up the cover when it is charged than if it were not charged; for, when charged, there is the tension of the electric field to be overcome as well as the force of gravity. Slightly harder work is done at the expense of the muscular energies of the operator; and this is the real origin of the energy stored up in the separate charges. The purely mechanical actions of putting down the disk on the cake, touching it, and lifting it up, can be performed automatically by suitable mechanical arrangements, which render the production of these inductive charges practically continuous. Of such continuous electrophori, the latest is Wimshurst's machine, described in Lesson V.

27. "Free" and "Bound" Electrification.—We have spoken of a charge of electricity on the surface of a conductor, as being "bound" when it is attracted by the presence of a neighbouring charge of the opposite kind. The converse term "free" is sometimes applied to the ordinary state of electricity upon a charged conductor, not in the presence of a charge of an opposite kind. A "free" charge upon an insulated conductor flows away instantaneously to the earth, if a conducting channel be provided, as will be explained. It is immaterial what point of the conductor be touched. Thus, in the case represented in Fig. 17, wherein a + electrified body induces − electrification at the near end, and + electrification at the far end of an insulated conductor, the − charge is "bound," being attracted, while the + charge at the other end, being repelled, is "free"; and if the insulated conductor be touched by a person standing on the ground, the "free" charge will flow away through his body to the earth, or to the walls of the room, while the "bound" charge will remain, no matter whether he touch the conductor at the far end, or at the near end, or at the middle.

28. Method of charging the Gold-Leaf Electroscope by Influence.—The student will now be prepared to understand the method by which a Gold-Leaf Electroscope can be charged with the opposite kind of charge to that of the electrified body used to charge it. In Lesson II. it was assumed that the way to charge an electroscope was to place the excited body in contact with the knob, and thus permit, as it were, a small portion of the charge to flow into the gold leaves. A rod of glass rubbed on silk being + would thus obviously impart + electrification to the gold leaves.

Suppose, however, the rubbed glass rod to be held a few inches above the knob of the electroscope, as is indeed shown in Fig. 12. Even at this distance the gold leaves diverge, and the effect is due to influence. The gold leaves, and the brass wire and knob, form one continuous conductor, insulated from the ground by the glass jar. The presence of the + charge of the glass acts inductively on this "insulated conductor," inducing − electrification on the near end or knob, and inducing + at the far end, *i.e.* on the gold leaves, which diverge. Of these two induced charges, the − on the knob is "bound," while the + on the leaves is "free." If now, while the excited rod is still held above the electroscope, the knob be touched by a person standing on the ground, one of these two induced charges flows to the ground, namely, the free charge—not that on the knob itself, for it was "bound," but that on the gold leaves which was "free"—and the gold leaves instantly drop down straight. There now remains only the − charge on the knob, "bound" so long as the + charge of the glass rod is near to attract it. But if, finally, the glass rod be taken right away, the − charge is no longer "bound" on the knob, but is "free" to flow into the leaves, which once more diverge—but this time with a *negative* electrification.

29. The "Return-Shock."—It is sometimes noticed that, when a charged conductor is suddenly discharged,

a discharge is felt by persons standing near, or may even affect electroscopes, or yield sparks. This action, known as the "return-shock," is due to influence. For in the presence of a charged conductor a charge of opposite sign will be induced in neighbouring bodies, and on the discharge of the conductor these neighbouring bodies may also suddenly discharge their induced charge into the earth, or into other conducting bodies. A "return-shock" is sometimes felt by persons standing on the ground at the moment when a flash of lightning has struck an object some distance away.

LESSON IV.—*Conduction and Distribution of Electricity*

30. Conduction.—Toward the close of Lesson I. we explained how certain bodies, such as the metals, conduct electricity, while others are non-conductors or insulators. This discovery is due to Stephen Gray; who, in 1729, found that a cork, inserted into the end of a rubbed glass tube, and even a rod of wood stuck into the cork, possessed the power of attracting light bodies. He found, similarly, that metallic wire and pack-thread conducted electricity, while silk did not.

We may repeat these experiments by taking (as in Fig. 25) a glass rod, fitted with a cork and a piece of wood. If a bullet or a brass knob be hung to the end of this by a linen thread or a wire, it is found that when the glass tube is rubbed the bullet acquires the property of attracting light bodies. If a dry silk thread is used, however, no electricity will flow down to the bullet.

Gray even succeeded in transmitting a charge of electricity through a hempen thread over 700 feet long, suspended on silken loops. A little later Du Fay succeeded in sending electricity to no less a distance than 1256 feet through a moistened thread, thus proving the conducting power of moisture. From that time the

classification of bodies into *conductors* and *insulators* has been observed.

This distinction cannot, however, be entirely maintained, as a large class of substances occupy an intermediate ground as partial conductors. For example, dry wood is a bad conductor and also a bad insulator; it is a good enough conductor to conduct away the high-potential electricity obtained by friction, but it is a bad conductor for the relatively low-potential electricity of small voltaic batteries. Substances that are very bad

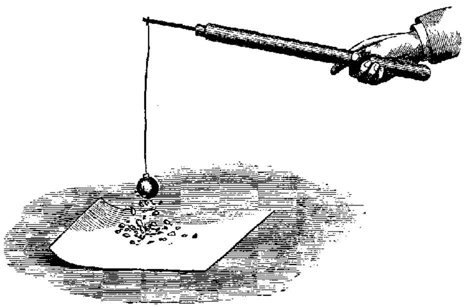


Fig. 25.

conductors are said to offer a great **resistance** to the flow of electricity through them. There is indeed no substance so good a conductor as to be devoid of resistance. There is no substance of so high a resistance as not to conduct a little. Even silver, which conducts best of all known substances, resists the flow of electricity to a small extent; and, on the other hand, such a non-conducting substance as glass, though its resistance is many million times greater than any metal, does allow a very small quantity of electricity to pass through it. In the

following list, the substances named are placed in order, each conducting better than those lower down on the list.

Silver	Good Conductors.
Copper	
Other metals	
Charcoal	
Water	
The body	Partial Conductors.
Cotton	
Dry wood	
Marble	
Paper	
Oils	Non-Conductors or Insulators.
Porcelain	
Wool	
Silk	
Resin	
Guttapercha	
Shellac	
Ebonite	
Paraffin	
Glass	
Quartz (fused)	
Air	

A simple way of observing experimentally whether a body is a conductor or not, is to take a charged gold-leaf electroscope, and, holding the substance to be examined in the hand, touch the knob of the electroscope with it. If the substance is a conductor the electricity will flow away through it and through the body to the earth, and the electroscope will be discharged. Through good conductors the rapidity of the flow is so great that the discharge is practically instantaneous. Further information on this question is given in Lesson XXXIII.

31. Distribution of Charge on Bodies.—If electrification is produced at one part of a non-conducting body, it remains at that point and does not flow over the surface, or at most flows over it excessively slowly.

Thus if a glass tube is rubbed at one end, only that one end is electrified. Hot glass is, however, a conductor. If a warm cake of resin be rubbed at one part with a piece of cloth, only the portion rubbed will attract light bodies, as may be proved by dusting upon it through a piece of muslin fine powders such as red lead, lycopodium, or verdigris, which adhere where the surface is electrified. The case is, however, wholly different when a charge of electricity is imparted to any part of a conducting body placed on an insulating support, for it *instantly* distributes itself all over the surface, though in general not uniformly over all points of the surface.

32. The Charge resides on the Surface.—A charge of electricity resides only on the surface of conducting bodies. This is proved by the fact that it is found to be immaterial to the distribution what the interior of a conductor is made of; it may be solid metal, or hollow, or even consist of wood covered with tinfoil or gilt, but, if the shape be the same, the charge will distribute itself precisely in the same manner over the surface. There are also several ways of proving by direct experiment this very important fact. Let a hollow metal ball, having an aperture at the top, be taken (as in Fig. 26), and set upon an insulating stem, and charged by sending into it a few sparks from an electrophorus. The absence of any charge in the interior may be shown as follows:—In order to observe the nature of the electrification of a charged body, it is convenient to have some means of removing a small quantity of the charge as a sample for examination. To obtain such a sample, a little instrument known as a **proof-plane** is employed. It consists of a little disk of sheet copper or of gilt paper fixed at the end of a small glass rod. If this disk is laid on the surface of an electrified body at any point, part of the charge flows into it, and it may be then removed, and the sample thus obtained may be examined with a gold-leaf electroscope in the ordinary way. For some

purposes a metallic bead, fastened to the end of a glass rod, is more convenient than a flat disk. If such a proof-plane be applied to the outside of our electrified hollow ball, and then touched on the knob of an electroscope, the gold leaves will diverge, showing the presence of a

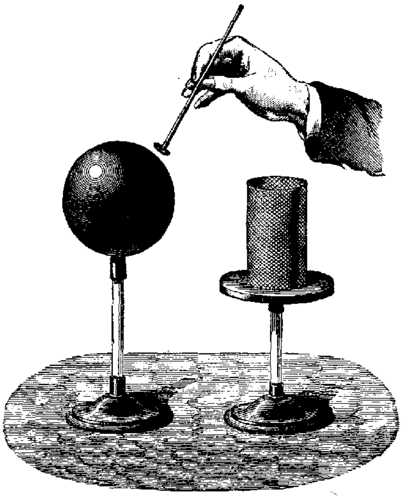


Fig. 26.

charge. But if the proof-plane be carefully inserted through the opening, and touched against the *inside* of the globe and then withdrawn, it will be found that the inside is destitute of electrification. An electrified pewter mug will show a similar result, and so will even a cylinder of gauze wire.

33. Biot's Experiment.—Biot proved the same fact in another way. A copper ball was electrified and insulated. Two hollow hemispheres of copper, of a larger size, and furnished with glass handles, were then placed together outside it (Fig. 27). So long as they did not come into contact the charge remained on the inner sphere; but if the outer shell touched the inner sphere for but an instant, the whole of the charge passed

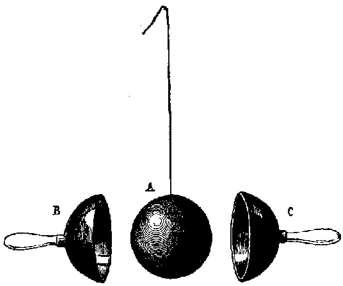


Fig. 27.

to the exterior; and when the hemispheres were separated and removed the inner globe was found to be completely discharged.

34. Further Explanation.—Doubtless the explanation of this behaviour of electricity is to be found in the property previously noticed as possessed by either kind of electrification, namely, that of repelling itself; hence it retreats as far as can be from the centre and remains upon the surface. An important proposition concerning the absence of electric force within a closed conductor is proved in Lesson XXI.; meanwhile it must be noted that the proofs, so far, are directed to demonstrate the absence

of a free charge of electricity in the interior of hollow conductors. Amongst other experiments, Terquem showed that a pair of gold leaves hung inside a wire cage could not be made to diverge when the cage was electrified. Faraday constructed a conical bag of linen-gauze, supported as in Fig. 28, upon an insulating stand, and to which silk strings were attached, by which it could be turned inside out. It was charged, and the charge was shown by the proof-plane and electroscope to be on the outside of the bag. On turning it inside out the elec-

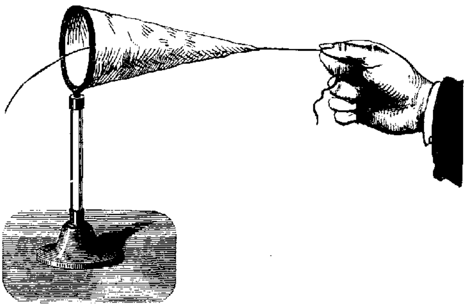


Fig. 28.

tricity was once more found *outside*. Faraday's most striking experiment was made with a hollow cube, measuring 12 feet each way, built of wood, covered with tinfoil, insulated, and charged with a powerful machine, so that large sparks and brushes were darting off from every part of its outer surface. Into this cube Faraday took his most delicate electroscopes; but once within he failed to detect the least effect upon them.

35. Applications.—Advantage is taken of this in the construction of delicate electrometers and other

instruments, which can be effectually screened from the influence of electrified bodies by enclosing them in a cover of thin metal, closed all round, except where apertures must be made for purposes of observation. Metal gauze answers excellently, and is nearly transparent. It was proposed by the late Professor Clerk Maxwell to protect buildings from lightning by covering them on the exterior with a network of wires.

36. Apparent Exceptions.—There are two apparent exceptions to the law that electrification resides only on the outside of conductors. (1) If there are electrified insulated bodies actually placed inside the hollow conductor, the presence of these electrified bodies acts inductively and attracts the opposite kind of charge to the inner side of the hollow conductor. (2) When electricity flows in a current, it flows through the substance of the conductor. The law is limited therefore to electricity at rest,—that is, to *statical* charges.

37. Faraday's "Ice-pail" Experiment.—One experiment of Faraday deserves notice, as showing the part played by induction in these phenomena. He gradually lowered a charged metallic ball into a hollow conductor connected by a wire to a gold-leaf electroscope (Fig. 29), and watched the effect. A pewter ice-pail being convenient for his purpose, this experiment is continually referred to by this name, though any other hollow conductor—a tin canister or a silver mug, placed on a glass support—would of course answer equally well. The following effects are observed:—Suppose the ball to have a + charge: as it is lowered into the hollow conductor the gold leaves begin to diverge, for the presence of the charge acts inductively, and attracts a − charge into the interior and repels a + charge to the exterior. The gold leaves diverge more and more until the ball is right within the hollow conductor, after which no greater divergence is obtained. On letting the ball touch the inside the gold leaves still remain diverging as

before, and if now the ball is pulled out it is found to have lost all its electrification. The fact that the gold leaves diverge no wider after the ball touched than they did just before, proves that when the charged ball is right inside the hollow conductor the induced charges are each of them precisely equal in amount to its own charge, and the interior negative charge exactly neutralizes the charge on the ball at the moment when they touch, leaving the equal exterior charge unchanged. An *electric cage*, such as this ice-pail, when connected with an electroscope or electrometer, affords an excellent means of examining the charge on a body small enough to be hung inside it. For without using up any of the charge of the body (which we are obliged to do when applying the method of the proof-plane) we can examine the induced charge repelled to the outside of the cage, which is equal in amount and of the same sign. If two equal charges of opposite kinds are placed at the same time within the cage no effects are produced on the outside.

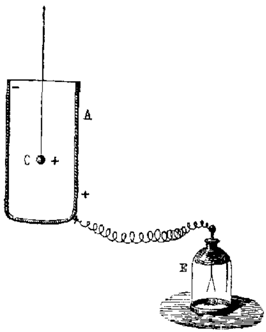


Fig. 29.

38. Distribution of Charge.—A charge of electricity is not usually distributed uniformly over the surfaces of bodies. Experiment shows that there is more electricity on the edges and corners of bodies than upon their flatter parts. This distribution can be deduced from the theory laid down in Lesson XXI., but meantime we will give some of the chief cases as they can be

shown to exist. The term **Electric Density** is used to signify the amount of electricity at any point of a surface; *the electric density at a point is the number of units of electricity per unit of area* (*i.e.* per square inch, or per square centimetre), the distribution being supposed uniform over this small surface.

(*a*) **Sphere.**—The distribution of a charge over an insulated sphere of conducting material is uniform, provided the sphere is also isolated, that is to say, is remote from the presence of all other conductors and all other electrified bodies. The density is uniform all over it. This is symbolized by the dotted line round the sphere in

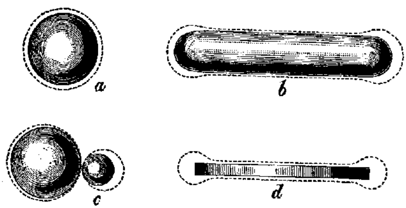


Fig. 30.

Fig. 30 *a*, which is at an equal distance from the sphere all round, suggesting an equal thickness of charge at every point of the surface. It must be remembered that the charge is not really of any perceptible thickness at all; it resides on or at the surface, but cannot be said to form a stratum upon it.

(*b*) **Cylinder with rounded Ends.**—Upon an elongated conductor, such as is frequently employed in electrical apparatus, the density is greatest at the ends where the curvature of the surface is the greatest.

(*c*) **Two Spheres in contact.**—If two spheres in contact with each other are insulated and charged, it is found that the density is greatest at the parts farthest

from the point of contact, and least in the crevice between them. If the spheres are of unequal sizes the density is greater on the smaller sphere, which has the surface more curved. On an **egg-shaped** or **pear-shaped** conductor the density is greatest at the small end. On a **cone** the density is greatest at the apex; and if the cone terminate in a sharp point the density there is very much greater than at any other point. At a **point**, indeed, the density of the collected electricity may be so great as to electrify the neighbouring particles of air, which then are repelled (see Art. 47), thus producing a continual loss of charge. For this reason points and sharp edges are always avoided on electrical apparatus, except where it is specially desired to set up a discharge.

(*d*) **Flat Disk.**—The density of a charge upon a flat disk is greater, as we should expect, at the edges than on the flat surfaces; but over the flat surfaces the distribution is fairly uniform.

These various facts are ascertained by applying a small proof-plane successively at various points of the electrified bodies and examining the amount taken up by the proof-plane by means of an electroscope or electrometer. Coulomb, who investigated mathematically as well as experimentally many of the important cases of distribution, employed the torsion balance to verify his calculations. He investigated thus the case of the ellipsoid of revolution, and found the densities of the charges at the extremities of the axis to be proportional to the lengths of those axes. He also showed that the density of the charge at any other point of the surface of the ellipsoid was proportional to the length of the perpendicular drawn from the centre to the tangent at that point. Riess also investigated several interesting cases of distribution. He found the density at the middle of the edges of a cube to be nearly two and a half times as great as the density at the middle of a face; while the density at a corner of the cube was more than four times as great.

39. Redistribution of Charge.—If any portion of the charge of an insulated conductor be removed, the remainder of the charge will immediately redistribute itself over the surface in the same manner as the original charge, provided it be also *isolated*, *i.e.* that no other conductors or charged bodies be near to perturb the distribution by complicated effects of influence.

If a conductor be charged with any quantity of electricity, and another conductor of the same size and shape (but uncharged) be brought into contact with it for an instant and then separated, it will be found that the charge has divided itself equally between them. In the same way a charge may be divided equally into three or more parts by being distributed simultaneously over three or more equal and similar conductors brought into contact and symmetrically placed.

If two equal metal balls, suspended by silk strings, charged with unequal quantities of electricity, are brought for an instant into contact and then separated, it will be found that the charge has redistributed itself fairly, half the sum of the two charges being now the charge of each. This may even be extended to the case of charges of opposite signs. Thus, suppose two similar conductors to be electrified, one with a positive charge of 5 units and the other with 3 units of negative charge, when these are made to touch and separated, each will have a positive charge of 1 unit; for the algebraic sum of $+5$ and -3 is $+2$, which, shared between the two equal conductors, leaves $+1$ for each.

40. Capacity of Conductors.—If the conductors be unequal in size, or unlike in form, the shares taken by each in this redistribution will not be equal, but will be proportional to the electric *capacities* of the conductors. The definition of **capacity** in its relation to electric quantities is given in Lesson XXI., Art. 271. We may, however, make the remark, that two insulated conductors of the same form, but of different sizes, differ in their

electrical *capacity;* for the larger one must have a larger amount of electricity imparted to it in order to electrify its surface to the same degree. The term *potential* is employed in this connection, in the following way :—A given quantity of electricity will electrify an isolated body up to a certain "potential" (or power of doing electric work) depending on its capacity. A large *quantity* of electricity imparted to a conductor of small *capacity* will electrify it up to a very high *potential;* just as a large quantity of water poured into a vessel of narrow capacity will raise the surface of the water to a high level in the vessel. The exact definition of Potential, in terms of energy spent against the electrical forces, is given in the lesson on Electrostatics (Art. 263).

It will be found convenient to refer to a positively electrified body as one electrified to a *positive or high potential;* while a negatively electrified body may be looked upon as one electrified to a *low or negative potential.* And just as we take the level of the sea as a zero level, and measure the heights of mountains above it, and the depths of mines below it, using the sea level as a convenient point of reference for differences of level, so we take the potential of the earth's surface (for the surface of the earth is always electrified to a certain degree) as *zero potential,* and use it as a convenient point of reference from which to measure differences of electric potential.

Lesson V.—*Electric Machines*

41. For the purpose of procuring larger supplies of electricity than can be obtained by the rubbing of a rod of glass or shellac, **electric machines** have been devised. All electric machines consist of two parts, one for producing, the other for collecting, the electric charges. Experience has shown that the quantities of + and −

electrification developed by friction upon the two surfaces rubbed against one another depend on the amount of friction, upon the extent of the surfaces rubbed, and also upon the nature of the substances used. If the two substances employed are near together on the list of electrics given in Art. 6, the electrical effect of rubbing them together will not be so great as if two substances widely separated in the series are chosen. To obtain the highest effect, the most positive and the most negative of the substances convenient for the construction of a machine should be taken, and the greatest available surface of them should be subjected to friction, the moving parts having a sufficient pressure against one another compatible with the required velocity.

The earliest form of electric machine was devised by Otto von Guericke of Magdeburg, and consisted of a globe of sulphur fixed upon a spindle, and pressed with the dry surface of the hands while being made to rotate; with this he discovered the existence of electric sparks and the repulsion of similarly electrified bodies. Sir Isaac Newton replaced Von Guericke's globe of sulphur by a globe of glass. A little later the form of the machine was improved by various German electricians; Von Bose added a collector or "prime conductor," in the shape of an iron tube, supported by a person standing on cakes of resin to insulate him, or suspended by silken strings; Winckler of Leipzig substituted a leathern cushion for the hand as a rubber; and Gordon of Erfurt rendered the machine more easy of construction by using a glass cylinder instead of a glass globe. The electricity was led from the excited cylinder or globe to the prime conductor by a metallic chain which hung over against the globe. A pointed collector was not employed until after Franklin's famous researches on the action of points. About 1760 De la Fond, Planta, Ramsden, and Cuthbertson, constructed machines having glass plates instead of cylinders. All frictional machines are, however, now

obsolete, having in recent years been quite superseded by the modern *Influence Machines*.

42. The Cylinder Electric Machine. — The Cylinder Electric Machine consists of a glass cylinder mounted on a horizontal axis capable of being turned by a handle. Against it is pressed from behind a cushion of leather stuffed with horsehair, the surface of which is covered with a powdered amalgam of zinc or tin. A flap of silk attached to the cushion passes over the cylinder, covering its upper half. In front of the cylinder stands the "prime conductor," which is made of metal, and

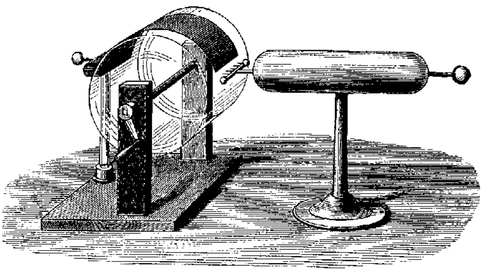


Fig. 31.

usually of the form of an elongated cylinder with hemispherical ends, mounted upon a glass stand. At the end of the prime conductor nearest the cylinder is fixed a rod bearing a row of fine metallic spikes, resembling in form a rake; the other end usually carries a rod terminated in a brass ball or knob. The general aspect of the machine is shown in Fig. 31. When the handle is turned the friction between the glass and the amalgam-coated surface of the rubber produces a copious electrical action, electricity appearing as a + charge on the glass, leaving the rubber with a – charge. The prime conductor collects

this charge by the following process:—The + charge being carried round on the glass acts inductively on the long insulated conductor, repelling a + charge to the far end; leaving the nearer end – ly charged. The effect of the row of points is to emit a – ly electrified wind (see Art. 47) towards the attracting + charge upon the glass, which is neutralized thereby; the glass thus arriving at the rubber in a neutral condition ready to be again excited. This action of the points is sometimes described, though less correctly, by saying that the points collect the + charge from the glass. If it is desired to collect also the – charge of the rubber, the cushion must be supported on an insulating stem and provided at the back with a metallic knob. It is, however, more usual to use only the + charge, and to connect the rubber by a chain to "earth," so allowing the – charge to be neutralized.

43. The Plate Electric Machine.—The Plate Machine, as its name implies, is constructed with a circular plate of glass or of ebonite, and is usually provided with two pairs of rubbers formed of double cushions, pressing the plate between them, placed at its highest and lowest point, and provided with silk flaps, each extending over a quadrant of the circle. The prime conductor is either double or curved round to meet the plate at the two ends of its horizontal diameter, and is furnished with two sets of spikes, for the same purpose as the row of

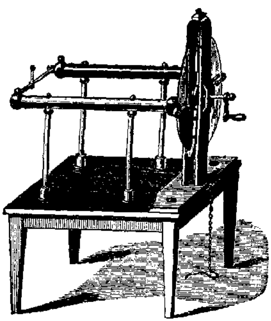


Fig. 32.

points in the cylinder machine. A common form of plate machine is shown in Fig. 32. The action of the machine is, in all points of theoretical interest, the same as that of the cylinder machine. Its advantages are that a large glass plate is more easy to construct than a large glass cylinder of perfect form, and that the length along the surface of the glass between the collecting row of points and the edge of the rubber cushions is greater in the plate than in the cylinder for the same amount of surface exposed to friction; for, be it remarked, when the two charges thus separated have collected to a certain extent, a discharge will take place along this surface, the length of which limits therefore the power of the machine. In a more modern form, due to Le Roy, and modified by Winter, there is but one rubber and flap, occupying a little over a quadrant of the plate, and one collector or double row of points, while the prime conductor consists of a ring-shaped body.

44. Electric Amalgam.—Canton, finding glass to be highly electrified when dipped into dry mercury, suggested the employment of an amalgam of tin with mercury as a suitable substance wherewith to cover the surface of the rubbers. Still better is Kienmayer's amalgam, consisting of equal parts of tin and zinc, mixed while molten with twice their weight of mercury. Bisulphide of tin ("mosaic gold") may also be used. These amalgams are applied to the cushions with a little stiff grease. They serve the double purpose of conducting away the negative charge separated upon the rubber during the action of the machine, and of affording as a rubber a substance which is more powerfully negative (see list in Art. 6) than the leather or the silk of the cushion itself. Powdered graphite is also good.

45. Precautions in using Frictional Machines.—Several precautions must be observed in the use of electrical machines. Damp and dust must be scrupulously avoided. The surface of glass is hygroscopic,

hence, except in the driest climates, it is necessary to warm the glass surfaces and rubbers to dissipate the film of moisture which collects. Glass stems for insulation may be varnished with a thin coat of shellac varnish, or with paraffin (solid). A few drops of anhydrous paraffin (obtained by dropping a lump of sodium into a bottle of paraffin oil), applied with a bit of flannel to the previously warmed surfaces, hinders the deposit of moisture. A frictional machine which has not been used for some months will require a fresh coat of amalgam on its rubbers. These should be cleaned and warmed, a thin uniform layer of tallow or other stiff grease is spread upon them, and the amalgam, previously reduced to a fine powder, is sifted over the surface. In spite of all precautions friction machines are uncertain in their behaviour in damp weather. This is the main reason why they have been superseded by influence machines, which do not need to be warmed.

All **points** should be avoided in apparatus for frictional electricity except where they are desired, like the "collecting" spikes on the prime conductor, to let off a charge of electricity. All the rods, etc., in frictional apparatus are therefore made with rounded knobs.

46. Experiments with the Electric Machine.—With the electric machine many pleasing and instructive experiments are possible. The phenomena of *attraction and repulsion* can be shown upon a large scale. Fig. 33 represents a device known as the **electric chimes,*** in which two small brass balls hung by silk strings are set in motion and strike against the bells between which they are hung. The two outer bells are hung by metallic wires or chains to the knob of the machine. The third bell is hung by a silk thread, but communicates with the ground by a brass chain. The balls are first attracted to

* Invented in 1752 by Franklin, for the purpose of warning him of the presence of atmospheric electricity, drawn from the air above his house by a pointed iron rod.

the electrified outer bells, then repelled, and, having discharged themselves against the uninsulated central bell, are again attracted, and so vibrate to and fro.

By another arrangement small figures or dolls cut out of pith can be made to dance up and down between a metal plate hung horizontally from the knob of the machine, and another flat plate an inch or two lower and communicating with "earth."

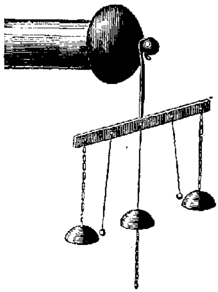


Fig. 33.

Another favourite way of exhibiting electric repulsion is by means of a doll with long hair placed on the machine; the individual hairs stand on end when the machine is worked, being repelled from the head, and from one another. A paper tassel will behave similarly if hung to the prime conductor. The most striking way of showing this phenomenon is to place a person upon a glass-legged stool, making him touch the knob of the machine; when the machine is worked, his hair, if dry, will stand on end. Sparks will pass freely between a person thus electrified and one standing upon the ground.

The sparks from the machine may be made to kindle spirits of wine or ether, placed in a metallic spoon, connected by a wire with the nearest metallic conductor that runs into the ground. A gas jet may be lit by passing a spark to the burner from the finger of the person standing, as just described, upon an insulating stool.

47. Effect of Points; Electric Wind.—The *effect of points* in discharging electricity from the surface of a conductor may be readily proved by numerous experiments.

If the machine be in good working order, and capable of giving, say, sparks 4 inches long when the knuckle is presented to the knob, it will be found that, on fastening a fine-pointed needle to the conductor, it discharges the electricity so effectually at its point that only the shortest sparks can be drawn at the knob, while a fine jet or brush of pale blue light will appear at the point. If a lighted taper be held in front of the point, the flame will be visibly blown aside (Fig. 34) by the streams of electrified air repelled from the point. These air-currents can be

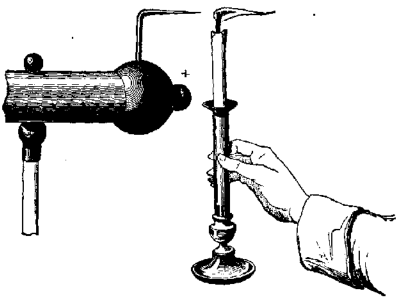


Fig. 34.

felt with the hand. They are due to a mutual repulsion between the electrified air particles near the point and the electricity collected on the point itself. That this mutual *reaction* exists is proved by the **electric fly** or **electric reaction-mill** of Hamilton (Fig. 35), which consists of a light cross of brass or straw, suspended on a pivot, and having the pointed ends bent round at right angles. When placed on the prime conductor of the machine, or joined to it by a chain, the force of repulsion between the electricity of the points and that on the air

immediately in front of them drives the mill round in the direction opposite to that in which the points are bent. It will even rotate if immersed in turpentine or petroleum. If the points of the fly are covered with small round lumps of wax it will not rotate, as the presence of the wax prevents the formation of any wind or stream of electrified particles.

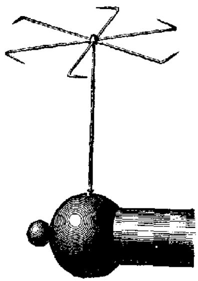


Fig. 35.

The electric wind from a point will produce a charge upon the surface of any insulating body, such as a plate of ebonite or glass, held a few inches away. The charge may be examined by dusting red lead or lycopodium powder upon the surface. If a slip of glass or mica be interposed between the point and the surface against which the wind is directed, an electric *shadow* will be formed on the surface at the part so screened.

48. Armstrong's Hydro-Electrical Machine.—The friction of a jet of steam issuing from a boiler, through a wooden nozzle, generates electricity. In reality it is the particles of condensed water in the jet which are directly concerned. Lord Armstrong, who investigated this source of electricity, constructed a powerful apparatus, known as the **hydro-electrical machine**, capable of producing enormous quantities of electricity, and yielding sparks 5 or 6 feet long. The collector consisted of a row of spikes, placed in the path of the steam jets issuing from wooden nozzles, and was supported, together with a brass ball which served as prime conductor, upon a glass pillar.

49. Influence Machines.—There is another class

of electrical machine, differing entirely from those we have been describing, and depending upon the principle of *influence.* They also have been termed *convection-induction machines,* because they depend upon the employment of a minute initial charge which, acting by influence, *induces* other charges, which are then *conveyed* by the moving parts of the machine to some other part, where they can be used either to increase the initial charge or to furnish a supply of electrification to a suitable collector. Of such instruments the oldest is the *Electrophorus*, explained fully in Lesson III. Bennet, Nicholson, Erasmus Darwin, and others devised pieces of apparatus for accomplishing by mechanism that which the electrophorus accomplishes by hand. Nicholson's *revolving doubler*, invented in 1788, consists of a revolving apparatus, in which an insulated carrier can be brought into the presence of an electrified body, there touched for an instant while under influence, then carried forward with its acquired charge towards another body, to which it imparts its charge, and which in turn acts inductively on it, giving it an opposite charge, which it can convey to the first body, thus increasing its initial charge at every rotation.

In the modern influence machines two principles are embodied: (1) the principle of *influence*, namely, that a conductor touched while under influence acquires a charge of the opposite kind; (2) the principle of *reciprocal accumulation.* This principle must be carefully noted. Let there be two insulated conductors A and B electrified ever so little, one positively, the other negatively. Let a third insulated conductor C, which will be called a *carrier*, be arranged to move so that it first approaches A and then B, and so forth. If touched while under the influence of the small positive charge on A it will acquire a small negative charge; suppose that it then moves on and gives this negative charge to B. Then let it be touched while under the influence of B, so acquiring a small positive charge. When it returns towards A let it give

up this positive charge to A, thereby increasing its positive charge. Then A will act more powerfully, and on repeating the former operations both B and A will become more highly charged. Each accumulates the charges derived by influence from the other. This is the fundamental action of the machines in question. The modern influence machines date from 1860, when C. F. Varley produced a form with six carriers mounted on a rotating disk of glass. This was followed in 1865 by

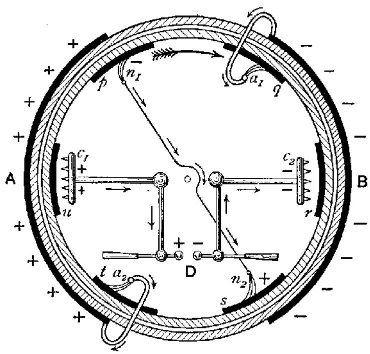


Fig. 36.

the machine of Holtz and that of Toepler, and in 1867 by those of Lord Kelvin (the "replenisher" and the "mouse-mill"). The latest forms are those of Mr. James Wimshurst.

50. Typical Construction. — Before describing some special forms we will deal with a generalized type of machine having two fixed *field-plates*, A and B, which are to become respectively + and −, and a set of *carriers*, attached to a rotating disk or *armature*. Fig. 36 gives in

a diagrammatic way a view of the essential parts. For convenience of drawing it is shown as if the metal field-plates A and B were affixed to the outside of an outer stationary cylinder of glass; the six carriers p, q, r, s, t, and u being attached to the inside of an inner rotating cylinder. The essential parts then are as follows:—

(i.) A pair of *field-plates* A and B.

(ii.) A set of *rotating carriers* p, q, r, s, t, and u.

(iii.) A pair of *neutralizing brushes* n_1, n_2 made of flexible metal wires, the function of which is to touch the carriers while they are under the influence of the field-plates. They are connected together by a *diagonal conductor*, which need not be insulated.

(iv.) A pair of *appropriating brushes* a_1, a_2, which reach over from the field-plates to appropriate the charges that are conveyed around by the carriers, and impart them to the field-plates.

(v.) In addition to the above, which are sufficient to constitute a complete self-exciting machine, it is usual to add a *discharging apparatus*, consisting of two *combs* c_1, c_2 to collect any unappropriated charges from the carriers after they have passed the appropriating brushes; these combs being connected to the adjustable discharging balls at D.

The operation of the machine is as follows. The neutralizing brushes are set so as to touch the moving carriers just before they pass out of the influence of the field-plates. Suppose the field-plate A to be charged ever so little positively, then the carrier p, touched by n_1 just as it passes, will acquire a slight negative charge, which it will convey forward to the appropriating brush a_1, and will thus make B slightly negative. Each of the carriers as it passes to the right over the top will do the same thing. Similarly each of the carriers as it passes from

right to left at the lower side will be touched by n_2 while under the influence of the $-$ charge on B, and will convey a small $+$ charge to A through the appropriating brush a_2. In this way A will rapidly become more and more $+$, and B more and more $-$; and the more highly charged they become, the more do the collecting combs c_1 and c_2 receive of unappropriated charges. Sparks will snap across between the discharging knobs at D.

The machine will not be self-exciting unless there is a good metallic contact made by the neutralizing brushes and by the appropriating brushes. If the discharging apparatus were fitted at c_1, c_2 with contact brushes instead of spiked combs, the machine would be liable to lose the charge of the field-plates, or even to have their charges reversed in sign whenever a large spark was taken from the knobs.

It will be noticed that there are two thicknesses of glass between the fixed *field-plates* and the rotating *carriers.* The glass serves not only to hold the metal parts, but prevents the possibility of back-discharges (by sparks or winds) from the carriers to the field-plates as they pass.

The essential features thus set forth will be found in Varley's machine of 1860, in Lord Kelvin's "replenisher" (which had only two carriers), and in many other machines, including the apparatus known as Clarke's "gas-lighter."

51. Toepler's Influence Machine. — In this machine, as constructed by Voss, are embodied various points due to Holtz and others. Its construction follows almost literally the diagram already explained, but instead of having two cylinders, one inside the other, it has two flat disks of varnished glass, one fixed, the other slightly smaller rotating in front of it (Fig. 37). The *field-plates* A and B consist of pieces of tinfoil, cemented on the back of the back disk, each protected by a coating of varnished paper. The *carriers* are small disks or sectors of tinfoil, to the number of six or eight, cemented to the front of the front disk. To prevent them from being worn away by rubbing against the brushes a small

metallic button is attached to the middle of each. The neutralizing brushes n_1, n_2 are small whisps of fine springy brass wire, and are mounted on the ends of a diagonal conductor Z. The appropriating brushes a_1, a_2 are also of thin brass wire, and are fastened to clamps projecting from the edge of the fixed disk, so that they communicate metallically with the two field-plates. The collecting combs, which have brass spikes so short as not to touch the carriers, are mounted on insulating pillars and are connected to the adjustable discharging knobs

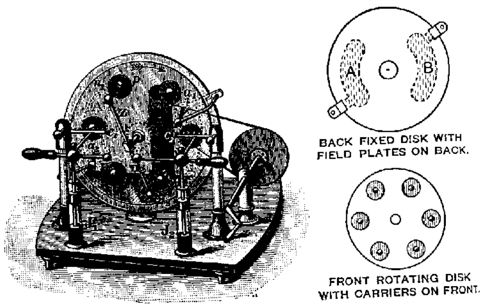


Fig. 37.

D_1, D_2. These also communicate with two small Leyden jars J_1, J_2, the function of which is to accumulate the charges before any discharge takes place. These jars are separately depicted in Fig. 38. Without them, the discharges between the knobs take place in frequent thin blue sparks. With them the sparks are less numerous, but very brilliant and noisy.

To use the Toepler (Voss) machine first see that all the four brushes are so set as to make good metallic contact with the carriers as they move past, and that the

neutralizing brushes are set so as to touch the carriers while under influence. Then see that the discharging knobs are drawn widely apart. Set the machine in rotation briskly. If it is clean it should excite itself after a couple of turns, and will emit a gentle hissing sound, due to internal discharges (visible as blue glimmers in the dark), and will offer more resistance to turning. If then the knobs are pushed nearer together sparks will pass across between them. The jars (the addition of which we owe to Holtz) should be kept free from dust. Sometimes a pair of terminal screws are added at S_1, S_2 (Fig. 38), connected respectively with the outer coatings

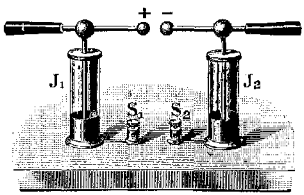


Fig. 38.

of the jars. These are convenient for attaching wires to lead away discharges for experiments at a distance. If not so used they should be joined together by a short wire, as the two jars will not work properly unless their outer coatings are connected.

52. Wimshurst's Influence Machine.—In this, the most widely used of influence machines, there are no fixed field-plates. In its simplest form it consists (Fig. 39) of two circular plates of varnished glass, which are geared to rotate in opposite directions. A number of sectors of metal foil are cemented to the front of the front plate and to the back of the back plate; these sectors serve both as carriers and as inductors. Across

the front is fixed an uninsulated diagonal conductor, carrying at its ends neutralizing brushes, which touch the front sectors as they pass. Across the back, but sloping the other way, is a second diagonal conductor, with brushes that touch the sectors on the hinder plate. Nothing more than this is needed for the machine to excite itself when set in rotation; but for convenience

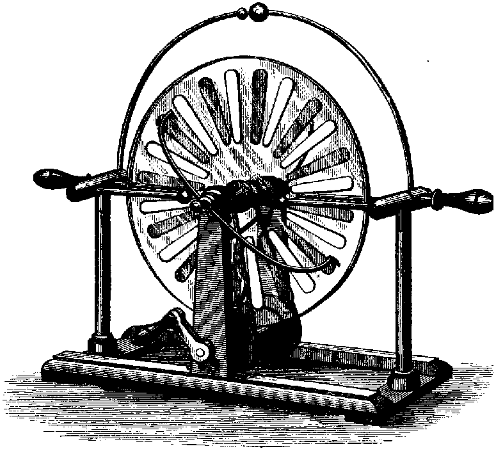


Fig. 39.

there is added a collecting and discharging apparatus. This consists of two pairs of insulated combs, each pair having its spikes turned inwards toward the revolving disks, but not touching them; one pair being on the right, the other on the left, mounted each on an insulating pillar of ebonite. These collectors are furnished with a pair of adjustable discharging knobs overhead; and

sometimes a pair of Leyden jars are added, to prevent the sparks from passing until considerable quantities of charge have been collected.

The processes that occur in this machine are best explained by aid of a diagram (Fig. 40), in which, for greater clearness, the two rotating plates are represented

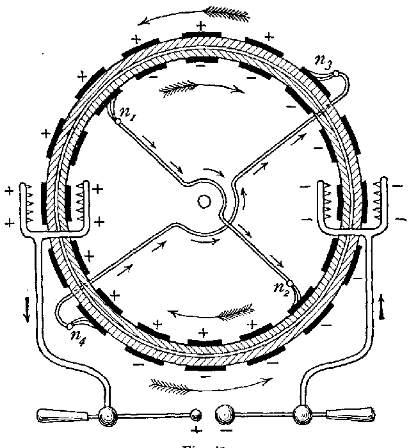


Fig. 40.

as though they were two cylinders of glass, rotating opposite ways, one inside the other. The inner cylinder will represent the front plate, the outer the back plate. In Figs. 39 and 40 the front plate rotates right-handedly, the back plate left-handedly. The neutralizing brushes n_1, n_2 touch the front sectors, while n_3, n_4 touch against the back sectors.

Now suppose any one of the back sectors represented near the top of the diagram to receive a slight positive charge. As it is moved onward toward the left it will come opposite the place where one of the front sectors is moving past the brush n_1. The result will be that the sector so touched while under influence by n_1 will acquire a slight negative charge, which it will carry onwards toward the right. When this negatively-charged front sector arrives at a point opposite n_3 it acts inductively on the back sector which is being touched by n_3; hence this back sector will in turn acquire a positive charge, which it will carry over to the left. In this way all the sectors will become more and more highly charged, the front sectors carrying over negative charges from left to right, and the back sectors carrying over positive charges from right to left. At the lower half of the diagram a similar but inverse set of operations will be taking place. For when n_1 touches a front sector under the influence of a positive back sector, a repelled charge will travel along the diagonal conductor to n_2, helping to charge positively the sector which it touches. The front sectors, as they pass from right to left (in the lower half), will carry positive charges, while the back sectors, after touching n_4, will carry negative charges from left to right. The metal sectors then act both as carriers and as inductors. It is clear that there will be a continual carrying of positive charges toward the right, and of negative charges to the left. At these points, toward which the opposite kinds of charges travel, are placed the collecting-combs communicating with the discharging knobs. The latter ought to be opened wide apart when starting the machine, and moved together after it has excited itself.

In larger Wimshurst influence machines two, three, or more pairs of oppositely-rotating plates are mounted within a glass case to keep off the dust. If the neutralizing brushes make good metallic contact these machines are all self-exciting in all weathers. Machines with only

six or eight sectors on each plate give longer sparks, but less frequently than those that have a greater number. Mr. Wimshurst has designed many influence machines, from small ones with disks 2 inches across up to that at South Kensington, which has plates 7 feet in diameter.

Prior to Wimshurst's machine Holtz had constructed one with two oppositely-rotating glass disks; but they had no metal carriers upon them. It was not self-exciting.

53. Holtz's Influence Machine.—The Holtz machine in its typical form had the following peculiarities. There were no metal carriers upon the rotating plate, hence another mode of charging it had to be adopted in lieu of touching conductors while under influence, as will be seen. The field-plates A and B (Fig. 41) were of varnished paper—a poor conductor—fastened upon the back of the fixed disk. In the fixed disk of glass, on which the field-plates were mounted, there were cut two windows or openings, through which there projected from the field-plates two pointed paper tongues, which took the place of appropriating brushes. The discharging knobs were inserted in the neutralizing circuit which united two metal combs with pointed spikes, situated in front of the rotating front disk, opposite the two field-plates. There was (at first) no diagonal conductor. It will be noted that while the combs, which served both as neutralizing and collecting combs, were in front of the rotating plate, the appropriating tongues were situated at the back of the same. Fig. 41 is a view of the machine from behind. The machine was not self-exciting. In operating it the following procedure

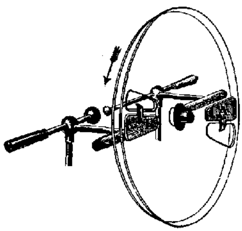


Fig. 41.

was used: first the two discharging knobs were put together, then the front disk was set into rapid rotation. While so rotating a small initial charge was communicated to one of the field-plates by holding to it a rubbed piece of ebonite or glass, or by sending into it a spark from a Leyden jar. Thereupon the machine charged itself, and began to emit pale blue sparks from the points of the combs and tongues with a hissing sound. On then drawing apart the discharging knobs, a torrent of sparks rushed across.

These arrangements being known, it is not difficult to follow the action of the machine, provided it is once understood that the whole operation depends upon the circumstance that the surface of a non-conducting body such as glass can be electrified by letting off against it an electric wind from a point placed near it (see Art. 47). Suppose that a small initial + charge is given to A. This will operate by influence upon the metal parts immediately opposite it, and cause the spikes to become electrified negatively, and to give off a negatively electrified wind, which will charge the face of the rotating plate, these charges being then carried over to the other side, where the spikes of the other comb will be emitting a positively electrified wind. The pointed tongues which project towards the back of the rotating disk also let off winds, the tendency being always for them to charge the back of the plate with a charge of opposite sign from that which is coming toward them on the front. If negative charges are being carried over the top on the front, then the tongue of B will tend to let off a positive charge against the back, thereby leaving B more negative. In the same way the tongue of A will let off a negatively electrified wind, making A more positive, so building up or accumulating two opposite kinds of charges on the two field-plates. This action will not occur unless the moving plate rotates in the direction opposite to that in which the two tongues point.

The defects of the Holtz machine were that it was so sensitive to damp weather as to be unreliable, that it was apt suddenly to reverse its charges, and that the electric winds by which it operated could not be produced without a sufficiently great initial charge.

In later Holtz machines a number of rotating disks fixed upon one common axis were employed, the whole being enclosed in a glass case to prevent the access of damp. A small disk of ebonite was sometimes fixed to the same axis, and provided with a rubber, in order to keep up the initial charge by friction. Holtz constructed many forms of machine, including one with thirty-two plates, besides machines of a second kind having two glass plates rotating in opposite directions.

The Holtz machine, as indeed every kind of influence machine, is *reversible* in its action; that is to say, that if a continuous supply of the two electricities (furnished by another machine) be communicated to the armatures, the movable plate will be thereby set in rotation and, if allowed to run quite freely, will turn in an opposite sense.

Righi showed that a Holtz machine can yield a continuous current like a voltaic battery, the strength of the current being nearly proportional to the velocity of rotation. It was found that the electromotive-force of a machine was equal to that of 52,000 Daniell's cells, or nearly 53,000 volts, at all speeds. The resistance when the machine made 120 revolutions per minute was 2810 million ohms; but only 646 million ohms when making 450 revolutions per minute.

54. Experiments with Influence Machines.—The experiments described in Art. 43, and indeed all those usually made with the old frictional machines, including the charging of Leyden jars, can be performed by the aid of influence machines. In some cases it is well to connect one of the two discharging knobs to the earth by a wire or chain, and to take the discharge from the other knob. To illuminate small vacuum tubes they

may be connected by guttapercha-covered wires to the two discharging knobs, or to the terminals S_1, S_2 of Fig. 38. The curious property of the electric discharge from a point in collecting *dust* or fumes is readily shown by connecting by a wire a needle which is introduced into a bell-jar of glass. The latter is filled with fumes by burning inside it a bit of magnesium wire or brown paper. Then on turning the handle of the influence machine the fumes are at once deposited, and the air left clear.

LESSON VI.—*The Leyden Jar and other Condensers*

55. It was shown in previous lessons that the opposite charges of electricity attract one another; that electricity cannot flow through glass; and that yet electricity can *act across* glass by influence. Two suspended pith-balls, one electrified positively and the other negatively, will attract one another across the intervening air. If a plate of glass be put between them they will still attract one another, though neither they themselves nor the electric charges on them can pass through the glass. If a pith-ball electrified with a − charge be hung inside a dry glass bottle, and a rubbed glass rod be held outside, the pith-ball will rush to the side of the bottle nearest to the glass rod, being attracted by the + charge thus brought near it. If a pane of glass be taken, and a piece of tinfoil be stuck upon the middle of each face of the pane, and one piece of tinfoil be charged positively, and the other negatively, the two charges will attract one another across the glass, and will no longer be found to be free. If the pane is set up on edge, so that neither piece of tinfoil touches the table, it will be found that hardly any electricity can be got by merely touching either of the foils, for the charges are "bound," so to speak, by each other's attractions; each charge is inducing the other. In fact it will be

found that these two pieces of tinfoil may be, in this manner, charged a great deal more strongly than either of them could possibly be if it were stuck to a piece of glass alone, and then electrified. In other words, *the capacity of a conductor is greatly increased when it is placed near to a conductor electrified with the opposite kind of charge.* If its capacity is increased, a greater quantity of electricity may be put into it before it is charged to an equal degree of potential. Hence, such an arrangement for holding a large quantity of electrification may be called a **condenser** of electricity.

56. Condensers.—Next, suppose that we have two brass disks, A and B (Fig. 42), set upon insulating stems, and that a glass plate is placed between them. Let B be connected by a wire to the knob of an electrical machine, and let A be joined by a wire to "earth." The + charge upon B will act inductively across the glass plate on A, and will repel electricity into the earth,

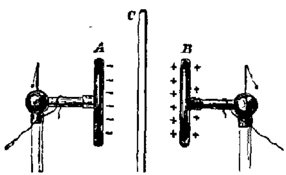


Fig. 42.

leaving the nearest face of A negatively electrified. This − charge on A will attract the + charge of B to the side nearest the glass, and a fresh supply of electricity will come from the machine. Thus this arrangement will become a condenser. If the two brass disks are pushed up close to the glass plate there will be a still stronger attraction between the + and − charges, because they are now nearer one another, and the inductive action will be greater; hence a still larger quantity can be accumulated in the plates. We see then that the capacity of a condenser is increased by bringing the plates near together. If now, while the disks are strongly charged, the wires are removed and the

disks are drawn backwards from one another, the two charges will not hold one another bound so strongly, and there will be more *free* electrification than before over their surfaces. This would be rendered evident to the experimenter by the little pith-ball electroscopes fixed to them (see the Fig.), which would fly out as the brass disks were moved apart. We have put no further charge on the disk B, and yet, from the indications of the electroscope, we should conclude that by moving it away from disk A it has become electrified to a higher degree. The fact is, that while the conductor B was near the – charge of A the *capacity* of B was greatly increased, but on moving it away from A its capacity has diminished, and hence the same quantity of electricity now electrifies it to a higher degree than before. The presence, therefore, of an earth-connected plate near an insulated conductor increases its capacity, and permits it to accumulate a greater charge by attracting and *condensing* the electricity upon the face nearest the earth-plate, the surface-density on this face being therefore very great; hence the appropriateness of the term *condenser* as applied to the arrangement. It was formerly also called an **accumulator**; but the term *accumulator* is now reserved for the special kind of battery for storing the energy of electric currents (Art. 492).

The stratum of *air* between the two disks will suffice *to insulate the two charges one from the other. The* brass disks thus separated by a stratum of air constitute an **air-condenser**, or **air-leyden**. Such condensers were first devised by Wilcke and Aepinus. In these experiments the sheet of glass or layer of air acts as a *dielectric* (Art. 295) conveying the inductive action through its substance. All dielectrics are insulators, but equally good insulators are not necessarily equally good dielectrics. Air and glass are far better insulators than ebonite or paraffin in the sense of being much worse conductors. But influence acts more strongly across a slab of glass than across a slab of ebonite or paraffin of equal thickness, and

better still across these than across a layer of air. In other words, glass is a better **dielectric** than ebonite, or paraffin, or air, as it possesses a higher inductive capacity.

It will then be seen that in the act of charging a condenser, as much electricity flows out at one side as flows in at the other.

57. Displacement.—Whenever electric forces act on a dielectric, tending to drive electricity in at one side and out at the other, we may draw lines of force through the dielectric in the direction of the action, and we may consider tubular spaces mapped out by such lines. We may consider a tube of electric force having at one end a definite area of the positively charged surface, and at the other end an area of the negatively charged surface. These areas may be of different size or shape, but the quantities of + and − electrification over them will be equal. The quantity of electricity which has apparently been transferred along the tube was called by Maxwell "the *displacement*." In non-conductors it is proportional to the electromotive-force. In conductors electromotive forces produce currents, which may be regarded as displacements which increase continuously with time. In certain crystalline media the displacement does not take place exactly in the direction of the electric force: in this case we should speak of tubes of influence rather than tubes of force. *A unit tube will be bounded at its two ends by unit charges + and −.* We may consider the whole electric field between positively and negatively charged bodies as mapped out into such tubes.

58. Capacity of a Condenser.—It appears, therefore, that the capacity of a condenser will depend upon—

(1) The size and form of the metal plates or coatings.

(2) The thinness of the stratum of dielectric between them; and

(3) The dielectric capacity of the material.

59. The Leyden Jar.—The Leyden Jar, called after the city where it was invented, is a convenient form of

condenser. It usually consists (Fig. 43) of a glass jar coated up to a certain height on the inside and outside with tinfoil. A brass knob fixed on the end of a stout brass wire passes downward through a lid or top of dry well-varnished wood, and communicates by a loose bit of brass chain with the inner coating of foil. To charge the jar the knob is held to the prime conductor of an electrical machine, the outer coating being either held in the hand or connected to "earth" by a wire or chain. When a + charge of electricity is imparted thus to the inner coating, it acts inductively on the outer coating, attracting a − charge into the face of the outer coating nearest the glass, and repelling a + charge to the outside of the outer coating, and thence through the hand or wire to earth. After a few moments the jar will have acquired its full charge, the outer coating being − and the inner +. If the jar is of good glass, and dry, and free from dust, it will retain its charge for many hours or days. But if a path be provided by which the two mutually attracting electricities can flow to one another, they will do so, and the jar will be instantaneously discharged. If the outer coating be grasped with one hand, and the knuckle of the other hand be presented to the knob of the jar, a bright spark will pass between the knob and the knuckle with a sharp report, and at the same moment a convulsive "shock" will be communicated to the muscles of the wrists, elbows, and shoulders. A safer means of discharging the jar is afforded by the **discharging tongs** or **discharger** (Fig. 44), which consists of a jointed brass rod provided with brass knobs and a glass handle. One knob is laid against the outer coating, the other is then

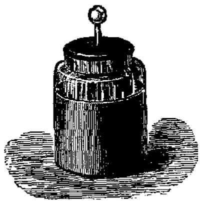


Fig. 43.

brought near the knob of the jar, and a bright snapping spark leaping from knob to knob announces that the two accumulated charges have flowed together, completing the discharge. Sometimes a jar discharges itself by a spark climbing over the top edge of the jar. Often when a jar is well charged a hissing sound is heard, due to partial discharges creeping over the edge. They can be seen in the dark as pale phosphorescent streams.

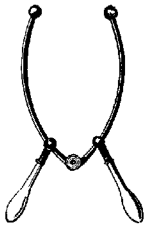


Fig. 44.

60. Discovery of the Leyden Jar.—The discovery of the Leyden jar arose from the attempt of Musschenbroek and his pupil Cuneus * to collect the supposed electric "fluid" in a bottle half filled with water, which was held in the hand and was provided with a nail to lead the "fluid" down through the cork to the water from the electric machine. Here the water served as an inner coating and the hand as an outer coating to the jar. Cuneus on touching the nail received a shock. This accidental discovery created the greatest excitement in Europe and America.

61. Residual Charges.—If a Leyden jar be charged and discharged and then left for a little time to itself, it will be found on again discharging that a small second spark can be obtained. There is in fact a **residual charge** which seems to have soaked into the glass or been absorbed. The return of the residual charge is hastened by tapping the jar. The amount of the residual charge varies with the time that the jar has been left charged; it also depends on the kind of glass of which the jar is made. There is no residual charge discoverable in an air-leyden after it has once been discharged.

* The honour of the invention of the jar is also claimed for Kleist, Bishop of Pomerania.

62. Batteries of Leyden Jars.—A large Leyden jar will give a more powerful shock than a small one, for a larger charge can be put into it; its capacity is greater. A Leyden jar made of *thin* glass has a greater capacity as a condenser than a thick one of the same size; but if it is too thin it will be destroyed when powerfully

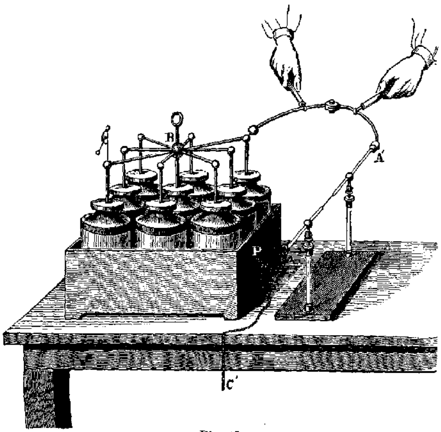


Fig. 45.

charged by a spark actually piercing the glass. "Toughened" glass is less easily pierced than ordinary glass, and hence Leyden jars made of it may be made thinner, and so will hold a greater charge. To prevent jars from being pierced by a spark, the highest part of the inside coating should be connected across by a strip of foil or a metallic disk to the central wire.

If a jar is desired to give *long sparks*, there must be

left a long space of varnished glass above the top of the coatings.

If it is desired to accumulate a very great charge of electricity, a number of jars must be employed, all their inner coatings being connected together, and all their outer coatings being united. This arrangement is called a **battery of Leyden jars**, or Leyden battery (Fig. 45). As it has a large capacity, it will require a large quantity of electricity to charge it fully. When charged it produces very powerful effects; its spark will pierce glass readily, and every care must be taken to avoid a shock from it passing through the person, as it might be fatal. The "Universal Discharger" as employed with the Leyden battery is shown at the right of the figure.

63. Seat of the Charge.—Benjamin Franklin discovered that the charges of the Leyden jar really reside on the surface of the glass, not on the metallic coatings. This he proved by means of a jar whose coatings could be removed (Fig. 46). The jar was charged and placed upon an insulating stand. The inner coating was then lifted out, and the glass jar was then taken out of the outer coating. Neither coating was found to be electrified to any extent, but on again putting the jar together it was found to be highly charged. The charges had all the time remained upon the inner and outer surfaces of the glass dielectric.

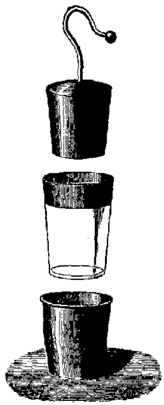


Fig. 46.

64. Dielectric Strain.—Faraday proved that the medium across which influence takes place really plays

an important part in the phenomena. It is now known that all dielectrics across which inductive actions are at work are thereby *strained.** Inasmuch as a good vacuum is a good dielectric, it is clear that it is not necessarily the material particles of the dielectric substance that are thus affected; hence it is believed that electrical phenomena are due to stresses and strains in the so-called "ether," the thin medium pervading all matter and all space, whose highly elastic constitution enables it to convey to us the vibrations of light though it is millions of times less dense than air. As the particles of bodies are intimately surrounded by ether, the strains of the ether are also communicated to the particles of bodies, and they too suffer a strain. The glass between the two coatings of tinfoil in the Leyden jar is actually strained or squeezed, there being a tension along the lines of electric force. When an insulated charged ball is hung up in a room an equal amount of the opposite kind of charge is attracted to the inside of the walls, and the air between the ball and the walls is **strained** (electrically) like the glass of the Leyden jar. If a Leyden jar is made of thin glass it may give way under the stress; and when a Leyden jar is discharged the layer of air between the knob of the jar and the knob of the discharging tongs is more and more strained as they are approached towards one another, till at last the stress becomes too great, and the layer of air gives way, and is "perforated" by the spark that discharges itself across. The existence of such stresses enables us to understand the residual charge of Leyden jars in which the glass does not recover itself all at once, by reason of its viscosity, from the strain to which it has been subjected. It must never be forgotten that **electric force acts across space in consequence of the transmission of stresses and**

* In the exact sciences a *strain* means an alteration of form or volume due to the application of a stress. A *stress* is the force, pressure, or other agency which produces a strain.

strains in the medium with which space is filled. In every case we store not electricity but *energy*. Work is done in pushing electricity from one place to another against the forces which tend to oppose the movement. The charging of a Leyden jar may be likened to the operation of bending a spring, or to pumping up water from a low level to a high one. In charging a jar we pump exactly as much electricity out of the negative side as we pump into the positive side, and we spend energy in so doing. It is this stored energy which afterwards reappears in the discharge.

LESSON VII.—*Other Sources of Electrification*

65. It was remarked at the close of Lesson I. (p. 13) that **friction** was by no means the only source of *electricity. Some of the other sources will now be* named.

66. Percussion.—A violent blow struck by one substance upon another produces opposite electrical states on the two surfaces. It is possible indeed to draw up a list resembling that of Art. 6, in such an order that each substance will take a + charge on being struck with one lower on the list.

67. Vibration.—Volpicelli showed that vibrations set up within a rod of metal coated with sulphur or other insulating substance, produced a separation of electricities at the surface separating the metal from the non-conductor.

68. Disruption and Cleavage.—If a card be torn asunder in the dark, sparks are seen, and the separated portions, when tested with an electroscope, will be found to be electrical. The linen faced with paper used in making strong envelopes and for paper collars, shows this very well. Lumps of sugar, crunched in the dark between the teeth, exhibit pale flashes of light.

The sudden cleavage of a sheet of mica also produces sparks, and both laminæ are found to be electrified.

69. Crystallization and Solidification.—Many substances, after passing from the liquid to the solid state, exhibit electrical conditions. Sulphur fused in a glass dish and allowed to cool is violently electrified, as may be seen by lifting out the crystalline mass with a glass rod. Chocolate also becomes electrical during solidification. When arsenic acid crystallizes out from its solution in hydrochloric acid, the formation of each crystal is accompanied by a flash of light, doubtless due to an electrical discharge. A curious case occurs when the sulphate of copper and potassium is fused in a crucible. It solidifies without becoming electrical, but on cooling a little further the crystalline mass begins to fly to powder with an instant evolution of electricity.

70. Combustion.—Volta showed that combustion generated electricity. A piece of burning charcoal, or a burning pastille, such as is used for fumigation, placed in connexion with the knob of a gold-leaf electroscope, will cause the leaves to diverge.

71. Evaporation.—The evaporation of liquids is often accompanied by electrification, the liquid and the vapour assuming opposite states, though apparently only when the surface is in agitation. A few drops of a solution of sulphate of copper thrown into a hot platinum crucible produce violent electrification as they evaporate.

72. Atmospheric Electricity.—The atmosphere is found to be always electrified relatively to the earth: this is due, in part possibly, to evaporation going on over the oceans. The subject of atmospheric electricity is treated of separately in Lesson XXV.

73. Pressure.—A large number of substances when compressed exhibit electrification on their surface. Thus cork becomes + when pressed against amber, guttapercha, and metals; while it takes a − charge when pressed

against spars and animal substances. Péclet found the degree of electrification produced by rubbing two substances together to be independent of the pressure and of the size of the surfaces of contact, but depended upon the materials and on the velocity with which they moved over one another. Rolling contact and sliding friction produced equal effects.

74. **Pyro-electricity.**—There are certain crystals which, while being heated or cooled, exhibit electrical charges at certain regions or poles. Crystals thus electrified by heating or cooling are said to be **pyro-electric.** Chief of these is the **Tourmaline,** whose power of attracting light bodies to its ends after being heated has been known for some centuries. It is alluded to by Theophrastus and Pliny under the name of *Lapis Lyncurius.* Tourmaline is a hard mineral, semi-transparent when cut into thin slices, and of a dark green or brown colour, but looking perfectly black and opaque in its natural condition, and possessing the power of polarizing light. It is usually found in slightly irregular three-sided prisms which, when perfect, are pointed at both ends. It belongs to the "hexagonal" system of crystals, but is only hemihedral, that is to say, has the alternate faces only developed. Its form is given in Fig. 47, where a general view is first shown, the two ends A and B being depicted in separate plans. These two ends differ slightly in shape. Each is made up of three sloping faces terminating in a point. But at A the edges between these faces run down to the corners of the prism, while in B the edges between the terminal faces run down to the middle points of the long faces of the prism. The end A is known as the **analogous** pole, and B as the **antilogous** pole. While the crystal is rising in temperature A exhibits + electrification, B – ; but if, after having been heated, it is allowed to cool, the polarity is reversed; for during the time that the temperature is falling B is + and A is –. If the

temperature is steady no such electrical effects are observed either at high or low temperatures; and the phenomena cease if the crystal be warmed above 150° C. This is not, however, due to the crystal becoming a conductor at that temperature; for its resistance at even higher temperatures is still so great as to make it practically a non-conductor. A heated crystal of tourmaline suspended by a silk fibre may be attracted and repelled by electrified bodies, or by a second heated tourmaline; the two similar poles repelling one another,

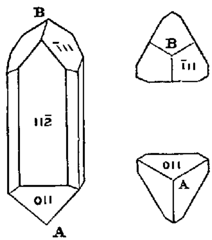


Fig. 47.

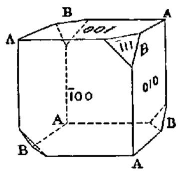


Fig. 48.

while the two poles of opposite form attract one another. If a crystal be broken up, each fragment is found to possess also an analogous and an antilogous pole.

Many other crystals beside the tourmaline are more or less pyro-electric. Amongst these are silicate of zinc ("electric calamine"), boracite, cane-sugar, quartz, tartrate of potash, sulphate of quinine, and several others. *Boracite* crystallizes in the form shown in Fig. 48, which represents a cube having four alternate corners truncated. The corners not truncated behave as analogous poles, the truncated ones as antilogous. When a natural hexagonal prism of quartz is heated its six edges are found to be + and − in alternate order.

75. Piezo-electricity.—In certain crystals pressure in a particular direction may produce electrification. Haüy found that a crystal of calcspar pressed between the dry fingers, so as to compress it along the blunt edges of the crystal, became electrical, and that it retained its electricity for some days. He even proposed to employ a squeezed suspended crystal as an electroscope. A similar property is alleged of mica, topaz, and fluorspar. If two opposite edges of a hexagonal prism of quartz are pressed together, one becomes +, the other −. Pressure also produces opposite kinds of electrification at opposite ends of a crystal of tourmaline, and of other crystals of the class already noticed as possessing the peculiarity of skew-symmetry or hemihedry in their structure. *Piezo-electricity* is the name given to this branch of the science. It is known that skew-symmetry of structure is dependent on molecular constitution; and it is doubtless the same peculiarity which determines the pyro-electric and piezo-electric properties, as well as the optical behaviour of these crystals in polarized light.

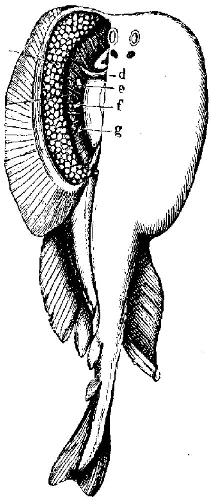


Fig. 49.

76. Animal Electricity.—Several species of creatures inhabiting the water have the power of producing electric discharges physiologically. The best known of these creatures are the *Torpedo*, the *Gymnotus*, and the

Silurus. The **Raia Torpedo,*** or electric ray, of which there are three species inhabiting the Mediterranean and Atlantic, is provided with an electric organ on the back of its head, as shown in Fig. 49. This organ consists of laminæ composed of polygonal cells to the number of 800 or 1000, or more, supplied with four large bundles of nerve fibres; the under surface of the fish is –, the upper +. In the **Gymnotus electricus**, or Surinam eel (Fig. 50), the electric organ goes the whole length of the body from tail to head. Humboldt gives a lively account

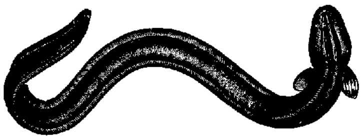


Fig. 50.

of the combats between the electric eels and the wild horses, driven by the natives into the swamps inhabited by the Gymnotus. It is able to give a most terrible shock, and is a formidable antagonist when it has attained its full length of 5 or 6 feet. In the **Silurus** the current flows from head to tail.

Nobili, Matteucci, and others, have shown that nerve-excitations and muscular contractions of human beings also give rise to feeble discharges of electricity.

77. Electricity of Vegetables.—Buff thought he detected electrification produced by plant life; the roots and juicy parts being negatively, and the leaves positively, electrified. The subject has, however, been little investigated.

* It is a curious point that the Arabian name for the torpedo, *ra-ad*, signifies *lightning*. This is perhaps not so curious as that the *Electra* of the Homeric legends should possess certain qualities that would tend to suggest that she is a personification of the *lightning*. The resemblance between the names *electra* and *electron* (amber) cannot be accidental.

78. Thermo-electricity.—*Heat* applied at the junction of two dissimilar metals produces a flow of electricity across the junction. This subject is discussed in Lesson XXXV. on *Thermo-electric Currents.*

79. Contact of Dissimilar Metals.—Volta showed that the contact of two dissimilar metals in air produced opposite kinds of electrification, one becoming positively, and the other negatively, electrified. This he proved in several ways, one of the most conclusive proofs being that afforded by his *condensing electroscope.* This consisted of a gold-leaf electroscope combined with a small condenser. A metallic plate formed he top of the electroscope, and on this was placed a second metallic plate fur-

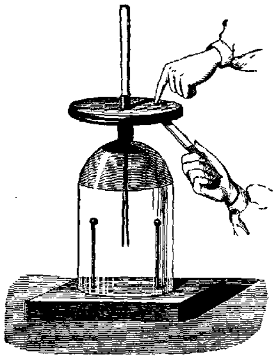


Fig. 51.

ished with a handle, and insulated from the lower one y being well varnished at the surface (Fig. 51). As the apacity of such a condenser is considerable, a very feeble ource may supply a quantity of electricity to the conenser without materially raising its potential, or causing ie gold leaves to diverge. But if the upper plate be lifted, ie capacity of the lower plate diminishes enormously, ıd the potential of its charge rises as shown by the vergence of the gold leaves.* To prove by the con-

* Formerly, this action was accounted for by saying that the electricity iich was "bound" when the plates of the condenser were close together,

densing electroscope that contact of dissimilar metals does produce electrification, a small compound bar made of two dissimilar metals—say zinc and copper—soldered together, is held in the moist hand, and one end of it is touched against the lower plate, the upper plate being placed in contact with the ground or touched with the finger. When the two opposing charges have thus collected in the condenser the upper plate is removed, and the diverging of the gold leaves shows the presence of a free charge, which can afterwards be examined to see whether it be + or −. Instead of employing the copper-zinc bar, a single voltaic cell may be connected by copper wires to the two plates. For a long time the existence of this electrification by contact was denied, or rather it was declared to be due (when occurring in voltaic combinations such as are described in Lesson XIII.) to chemical actions going on; whereas the real truth is that the electricity of contact and the chemical action are both due to molecular conditions of the substances which come into contact with one another, though we do not yet know the precise nature of the molecular conditions which give rise to these two effects. Later experiments, especially those made with the modern delicate electrometers of Lord Kelvin, put beyond doubt the reality of Volta's discovery. One simple experiment explains the method adopted. A thin strip or needle of metal is suspended so as to turn about a point C. It is electrified from a known source. Under it are placed (Fig. 52) two semicircular disks, or half-rings of dissimilar

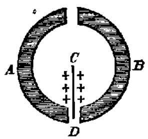


Fig. 52.

becomes "free" when the top plate is lifted up; the above is, however, a more scientific and more accurate way of saying the same thing. The student who is unable to reconcile these two ways of stating the matter should read again Articles 40 and 55, on pp. 46 and 68. A much more sensitive apparatus to show the effect is the quadrant electrometer (Art. 288).

metals. Neither attracts or repels the electrified needle until the two are brought into contact, or connected by a third piece of metal, when the needle immediately turns, being attracted by the one that is oppositely electrified, and repelled by the one that is electrified similarly with itself.

80. Contact Series of Metals (in Air).—Volta found, moreover, that the differences of electric potential between the different pairs of metals were not all equal. Thus, while zinc and lead were respectively + and − to a slight degree, he found zinc and silver to be respectively + and − to a much greater degree. He was able to arrange the metals in a series such that each one enumerated became positively electrified when placed in contact in air with one below it in the series. Those in italics are added from observations made since Volta's time—

+ *Sodium*,	Copper,
Magnesium,	Silver,
Zinc,	Gold,
Lead,	*Platinum*,
Tin,	− *Graphite* (Carbon).
Iron,	

Though Volta gave rough approximations, the actual numerical values of the differences of potential in air for different pairs of metals have only lately been measured by Ayrton and Perry, a few of whose results are tabulated here—

	Difference of Potential (volts).
Zinc – Lead	·210
Lead – Tin	·069
Tin – Iron	·313
Iron – Copper	·146
Copper – Platinum	·238
Platinum – Carbon	·113

The difference of potential between zinc and carbon is the same as that obtained by adding the successive differences, or 1·09 volts.* Volta's observations may therefore be stated in the following generalized form, known as **Volta's Law.** *The difference of potential between any two metals is equal to the sum of the differences of potentials between the intervening metals in the contact-series.*

It is most important to notice that the order of the metals in the contact-series *in air* is almost identical with that of the metals arranged according to their electro-chemical power, as calculated from their chemical equivalents and their heat of combination with oxygen (see Table, Art. 489). From this it would appear that the difference of potentials between a metal and the air that surrounds it measures the tendency of that metal to become oxidized by the air. If this is so, and if (as is the case) the air is a bad conductor while the metals are good conductors, it ought to follow that when two different metals touch they equalize their own potentials by conduction but leave the films of air that surround them at different potentials. All the exact experiments yet made have measured the difference of potentials not between the metals themselves, but between the air near one metal and that near another metal. Mr. John Brown has shown that while in air iron is positive to copper, but in an atmosphere of sulphuretted hydrogen, iron is negative to copper. He has also demonstrated the existence on freshly-cleaned metal surfaces of *films* of liquid or condensed gases, and has shown that polished zinc and copper, when brought so near that their films touch, will act as a battery.

81. Contact Actions.—A difference of potential is also produced by the contact of *two dissimilar liquids* with one another.

* For the definition of the *volt*, or unit of difference of potential, see Art. 254.

A *liquid and a metal* in contact with one another also exhibit a difference of potential, and if the metal tends to dissolve into the liquid chemically there will be an electromotive force acting from the metal toward the liquid.

The thermo-electric difference of potential at a junction of two metals is a true contact difference. It is measured by the amount of heat produced (see *Peltier-effect*, Art. 420) by passing a current of electricity in the reverse direction through the junction.

A *hot* metal placed in contact with a *cold* piece of the same metal also produces a difference of potential, electrical separation taking place across the surface of contact.

Lastly, it has been shown by Professor J. J. Thomson that the surface of contact between two non-conducting substances, such as sealing-wax and glass, is the seat of a permanent difference of potentials.

82. Magneto-electricity.—Electric currents flowing along in wires can be obtained from magnets by moving closed conducting circuits in their neighbourhood. This source is dealt with in Art. 222, Lesson XVIII.

83. Summary.—We have seen in the preceding paragraphs how almost all conceivable agencies may produce electrification in bodies. The most important of these are friction, heat, chemical action, magnetism, and the contact of dissimilar substances. We noted that the production of electricity by friction depended largely upon the molecular condition of the surfaces. We may here add that the difference of potentials produced by contact of dissimilar substances also varies with the temperature and with the nature of the medium (air, vacuum, etc.) in which the experiments are made. Doubtless this source also depends upon the molecular conditions of dissimilar substances being different; the particles at the surfaces being of different sizes and

shapes, and vibrating with different velocities and with different forces. There are (see Art. 10) good reasons for thinking that the electricity of friction is really due to electricity of contact, excited at successive portions of the surfaces as they are moved over one another. But of the molecular conditions of bodies which determine the production of electrification where they come into contact, little or nothing is yet known.

CHAPTER II

MAGNETISM

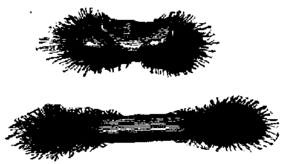
LESSON VIII.—*Magnetic Attraction and Repulsion*

84. Lodestones or Natural Magnets.—The name **Magnet** (*Magnes Lapis*) was given by the ancients to certain hard black stones found in various parts of the world, notably at *Magnesia* in Asia Minor, which possessed the property of attracting to them small pieces of iron. This magic property, as they deemed it, made the magnet-stone famous ; but it was not until the tenth or twelfth century that such stones were discovered to have the still more remarkable property of pointing north and south when hung up by a thread. This property was turned to advantage in navigation, and from that time the magnet received the name of **Lodestone** * (or "leading-stone"). The natural magnet or lodestone is an ore of iron, known to mineralogists as *magnetite* and having the chemical composition Fe_3O_4. This ore is found in quantities in Sweden, Spain, the Isle of Elba, Arkansas, and other parts of the world, though not always in the magnetic condition. It frequently occurs in crystals ; the usual form being the regular octahedron.

85. Artificial Magnets.—If a piece of hard iron be rubbed with a lodestone, it will be found to have also

* The common spelling *load*stone is due to misapprehension.

acquired the properties characteristic of the stone; it will attract light bits of iron, and if hung up by a thread it will point north and south. Savery, in 1729, first showed how much more retentive of magnetism hardened steel is than mere iron. Figs. 53 and 54 represent a natural lodestone and an artificial magnet of steel, each of which has been dipped into iron-filings; the filings are attracted and adhere in tufts.



Figs. 53 and 54.

86. Writings of Dr. Gilbert.—This was all, or nearly all, that was known of the magnet until 1600, when Dr. Gilbert published a large number of magnetic discoveries in his famous work *De Magnete*. He observed that the attractive power of a magnet appears to reside at two regions, and in a long-shaped magnet these regions, or **poles**, are usually at the ends (see Figs. 53 and 54). The portion of the magnet which lies between the two poles is apparently less magnetic, and does not attract iron-filings so strongly; and all round the magnet, halfway between the poles, there is no attraction at all. This region Gilbert called the **equator** of the magnet, and the imaginary line joining the poles he termed the **axis**.

87. Magnetic Needle.—To investigate more fully the magnetic forces a **magnetic needle** is employed. This consists (Fig. 55) of a light needle cut out of steel, and fitted with a little cap of brass, glass, or agate, by means of which it can be hung upon a sharp point, so as to turn with very little friction. It is rendered magnetic by being rubbed upon a magnet; and when thus magnetized it will turn into the north-and-south

position, or, as we should say, will set itself in the "magnetic meridian" (Art. 151). The *compass* sold by opticians consists of such a needle balanced above a card marked with the "points of the compass."

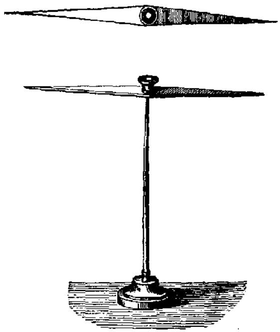


Fig. 55.

88. Magnetic Attractions and Repulsions.—If we take a magnet (either natural or artificial) in our hand and present the two "poles" of it successively to the north-pointing end of a magnetic needle, we shall observe that one pole of the magnet *attracts* it, while the other *repels* it (Fig. 56). Repeating the experiment on the south-pointing end of the magnetic needle, we find that it is *repelled* by one pole and *attracted* by the other; and that the same pole which attracts the north-pointing end of the needle repels the south-pointing end.

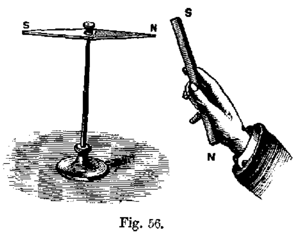


Fig. 56.

If we try a similar experiment on the magnetic needle, using for a magnet a second magnetized needle which has

previously been suspended, and which has its north-pointing end *marked* to distinguish it from the south-pointing end, we shall discover that the N-pointing pole repels the N-pointing pole, and that the S-pointing pole repels the S-pointing pole; but that a N-pointing pole attracts and is attracted by a S-pointing pole.

89. Two Kinds of Magnetic Poles.—There would therefore appear to be two opposite kinds of magnetism, or at any rate two opposite kinds of magnetic poles, which attract or repel one another in very much the same fashion as the two opposite kinds of electrification do; and one of these kinds of magnetism appears to have a tendency to move toward the north and the other to move toward the south. It has been proposed to call these two kinds of magnetism "north-seeking magnetism" and "south-seeking magnetism", but for our purpose it is sufficient to distinguish between the two kinds of poles. In common parlance the poles of a magnet are called the "North Pole" and "South Pole" respectively, and it is usual for the makers of magnets to mark the N-pointing pole with a letter N. It is therefore sometimes called the "marked" pole, to distinguish it from the S-pointing or "unmarked" pole. We shall, to avoid any doubt,* call that pole of a magnet which would, if the magnet were suspended, tend to turn to the north, the "North-seeking" pole, and the other the "South-seeking" pole.

We may therefore sum up our observations in the con-

* It is necessary to be precise on this point, as there is some confusion in the existing text-books. The cause of the confusion is this:—If the north-pointing pole of a needle is *attracted* by magnetism residing near the North Pole of the earth, the law of attraction (that *unlike poles attract*) shows us that these two poles are really magnetically of opposite kinds. Which are we then to call north magnetism? That which is at the N pole of the earth? If so, we must say that the N-pointing pole of the needle contains south magnetism. And if we call that north magnetism which points to the north, then we must suppose the magnetic pole at the north pole of the earth to have south magnetism in it. In either case there is

cise statement: *Like magnetic poles repel one another; unlike poles attract one another.* This we may call the first law of magnetism. As with the electric attractions and repulsions of rubbed bodies, so with these magnetic attractions and repulsions the effects are due, as we shall see, to stresses in the intervening medium.

90. The two Poles inseparable.—It is impossible to obtain a magnet with only one pole. If we magnetize a piece of steel wire, or watch spring, by rubbing it with one pole of a magnet, we shall find that still it has two poles—one N-seeking, the other S-seeking. And if we break it into two parts, each part will still have two poles of opposite kinds.

91. Magnetic Force.—The force with which a magnet attracts or repels another magnet, or any piece of iron or steel, we shall call *magnetic force.** The force exerted by a magnet upon a bit of iron or on another magnet is not the same at all distances, the force being greater when the magnet is nearer, and less when the magnet is farther off. (See Art. 128, on laws of magnetic force.)

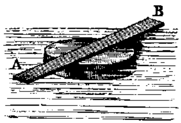


Fig. 57.

Whenever a force acts thus between two bodies, it acts on both of them, tending to move both. A magnet will attract a piece of iron, and a piece of iron will attract a magnet. This was shown by Sir Isaac Newton, who

then a difficulty. The Chinese and the French call the N-pointing pole of the needle a south pole, and the S-pointing pole a north pole. Lord Kelvin also calls the N-pointing pole a "True South" pole. But common practice goes the other way, and calls the N-pointing pole of a magnet its "North" pole. For experimental purposes it is usual to paint the two poles of a magnet of different colours, the N-seeking pole being coloured *red* and the S-seeking pole *blue;* but here again, strangely enough, authorities differ, for in the collections of apparatus at the Royal Institution and Royal School of Mines, the colours are used in exactly the opposite way to this, which is due to Airy.

* See footnote on "Force," Art. 169.

fixed a magnet upon a piece of cork and floated it in a basin of water (Fig. 57), and found that it moved across the basin when a piece of iron was held near. A compass needle thus floated turns round and points north and south ; but it does not rush towards the north as a whole, nor towards the south. The reason of this will be explained later, in Art. 129.

Gilbert suggested that the force of a magnet might be measured by making it attract a piece of iron hung to one arm of a balance, weights being placed in the scale-pan hanging to the other arm ; and he found, by hanging the *magnet* to the balance and placing the *iron* beneath it, that the effect produced was the same. The action and reaction are then equal for magnetic forces.

92. Magnetic Substances.—A distinction was drawn by Gilbert between *magnets* and *magnetic substances.* A magnet attracts only at its poles, and they possess opposite properties. But a lump of iron will attract either pole of the magnet, no matter what part of the lump be presented to the magnet. It has no distinguishable fixed "poles," and no magnetic "equator." A true magnet has poles, one of which is *repelled* by the pole of another magnet.

93. Other Magnetic Metals.—Later experimenters have extended the list of substances which are attracted by a magnet. In addition to iron (and steel) the following metals are recognized as magnetic, viz., nickel and cobalt. Some of their alloys with iron are also magnetic. It has also been supposed that chromium, cerium, and palladium are slightly magnetic, but further investigation has shown this to be erroneous. But only nickel and cobalt are at all comparable with iron and steel in magnetic power, and even they are very far inferior. Other bodies, sundry salts of iron and other metals, paper, porcelain, and oxygen gas are also very feebly attracted by a powerful magnet. Liquid oxygen is attracted to the poles of magnets.

94. Diamagnetism.—A number of bodies, notably bismuth, antimony, phosphorus, and copper, are apparently repelled from the poles of a magnet. Such bodies are called *diamagnetic bodies;* a fuller account of them will be found in Lesson XXIX.

95. The Earth a Magnet. — The greatest of Gilbert's discoveries was that of the inherent magnetism of the earth. *The earth is itself a great magnet,* whose "poles" coincide nearly, but not quite, with the geographical north and south poles, and therefore it causes a freely-suspended magnet to turn into a north-and-south position. Gilbert had some lodestones cut to the shape of spheres to serve as models of the globe of the earth. Such a globular magnet he called a *terrella.* He found that small magnets turned toward the poles of the terrella, and dip, as compass-needles do, toward the earth.

The subject of *Terrestrial Magnetism* is treated of in Lesson XII. It is evident from the first law of magnetism that the magnetic condition of the northern regions of the earth must be the opposite to that of the north-seeking pole of a magnetized needle. Hence arises the difficulty alluded to on page 92.

96. Induction of Magnetism.—Magnetism may be communicated to a piece of iron without actual contact

Fig. 58.

with a magnet. If a short, thin unmagnetized bar of iron be placed near some iron filings, and a magnet be brought near to the bar, the presence of the magnet will *induce* magnetism in the iron bar, and it will now attract the iron filings (Fig. 58). This inductive action is very similar to that observed in Lesson III. to take place when a non-electrified body was brought under the influence of

an electrified one. The analogy, indeed, goes further than this, for it is found that the iron bar thus magnetized by induction will have two poles ; the pole nearest to the pole of the inducing magnet being of the opposite kind, while the pole at the farther end of the bar is of the same kind as the inducing pole. Those bodies in which a magnetizing force produces a high degree of magnetization are said to possess a high *permeability*. It will be shown presently that magnetic induction takes place along certain directions called *lines of magnetic induction*, or *lines of magnetic force*, which may pass either through iron and other magnetic media, or through air, vacuum, glass, or other non-magnetic media: and, since induction goes on most freely in bodies of high magnetic permeability, the magnetic lines are sometimes (though not too accurately) said to "pass by preference through magnetic matter," or, that "magnetic matter conducts the lines of force."

97. Attraction across Bodies.—If a sheet of glass, or wood, or paper, be interposed between a magnet and the piece of iron or steel it is attracting, it will still attract it as if nothing were interposed. A magnet sealed up in a glass tube still acts as a magnet. Lucretius found a magnet put into a brass vase attracted iron filings through the brass. Gilbert surrounded a magnet by a ring of flames, and found it still to be subject to magnetic attraction from without. Across water, vacuum, and all known substances, the magnetic forces will act ; with the single apparent exception, however, that magnetic force will not act across a *screen of iron* or other magnetic material, if sufficiently thick. If a small magnet is suspended inside a hollow ball made of iron, no outside magnet will affect it, the reason being that the magnetic lines of force are conducted off laterally through the iron instead of penetrating through it. A hollow shell of iron will therefore act as a *magnetic cage*, and shield the space inside it from magnetic influences.

Fig. 59 illustrates the way in which a cylinder of soft iron shields the space interior to it from the influence of an external magnet. A compass needle placed at P inside the cylinder is not affected by the presence of the magnet outside, for its lines of magnetic force are drawn off laterally. Similarly a magnet inside is shielded from affecting outside space.

Although magnetic induction takes place at a distance across an intervening layer of air, glass, or vacuum, there is no doubt that the intervening medium is directly concerned in the transmission of the magnetic force, though

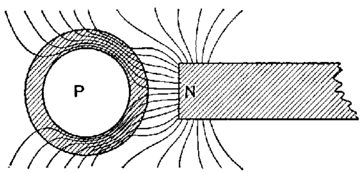


Fig. 59.

the true medium is probably the "ether" of space surrounding the molecules of matter, not the molecules themselves.

We now can see why a magnet should attract a not-previously-magnetized piece of iron; it first magnetizes it by induction and then attracts it: for the nearest end will have the opposite kind of magnetism induced in it, and will be attracted with a force exceeding that with which the more distant end is repelled. But *induction precedes attraction.*

98. Retention of Magnetization.—Not all magnetic substances can become magnets permanently. Lodestone, steel, and nickel retain permanently the greater part of the magnetism imparted to them. Cast iron and many impure qualities of wrought iron also

retain magnetism imperfectly. The softer and purer a specimen of iron is, the more lightly is its residual magnetism retained. The following experiment illustrates the matter:—Let a few pieces of iron rod, or a few soft iron nails be taken. If one of these (see Fig. 60) be placed in contact with the pole of a permanent steel magnet, it is attracted to it, and becomes itself a temporary magnet. Another bit of iron may then be hung to it, and another, until a chain of four or five pieces is built up. But if the steel magnet be removed from the top of the chain, all the rest drop off, and are found to be no longer magnetic. A similar chain of steel needles may be formed, but they will retain permanently most of their magnetism.

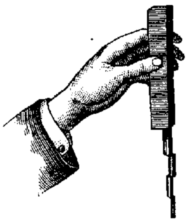


Fig. 60.

It will be found, however, that a steel needle is more difficult to magnetize than an iron needle of the same dimensions. It is harder to get the magnetism *into* steel than into iron, and it is harder to get the magnetism *out* of steel than out of iron; for the steel retains the magnetism once put into it. This power of resisting magnetization or demagnetization is sometimes called *coercive force;* a much better term, due to Lamont, is **retentivity**. The retentivity of hard-tempered steel is great; that of soft wrought iron is very small. The harder the steel, the greater its retentivity. Form affects retentivity. Elongated forms and those shaped as closed or nearly closed circuits retain their magnetism better than short rods, balls, or cubes.

99. Theories of Magnetism.—The student will not have failed to observe the striking analogies between the phenomena of attraction, repulsion, induction, etc., of magnetism and those of electricity. Yet the two sets

of phenomena are quite distinct. A positively electrified body does not attract either the North-pointing or the South-pointing pole of the magnet as such ; in fact, it attracts either pole quite irrespective of its magnetism, just as it will attract any other body. There does exist, indeed, a direct relation between magnets and *currents* of electricity, as will be later explained. There is none known, however, between magnets and stationary *charges* of electricity.

In many treatises it is the fashion to speak of a **magnetic fluid** or fluids ; it is, however, *absolutely certain that magnetism is not a fluid*, whatever else it may be. The term is a relic of bygone times. A magnet when rubbed upon a piece of steel magnetizes it *without giving up or losing any of its own magnetism*. A fluid cannot possibly propagate itself indefinitely without loss. The arguments to be derived from the behaviour of a magnet on breaking, and from other experiments narrated in Lesson X., are even stronger. No theory of magnetism will therefore be propounded until these facts have been placed before the student.

LESSON IX.—*Methods of making Magnets*

100. Magnetization by Single Touch.—It has been so far assumed that bars or needles of steel were to be magnetized by simply touching them, or stroking them from end to end with the pole of a permanent magnet of lodestone or steel. In this case the last touched point of the bar will be a pole of opposite kind to that used to touch it ; and a more certain effect is produced if one pole of the magnet be rubbed on one end of the steel needle, and the other pole upon the other end. There are, however, better ways of magnetizing a bar or needle.

101. Magnetization by Divided Touch.—In this method the bar to be magnetized is laid down

horizontally; two bar magnets are then placed down upon it, their opposite poles being together. They are then drawn asunder from the middle of the bar towards its ends, and back, several times. The bar is then turned over, and the operation repeated, taking care to leave off at the middle (see Fig. 61). The process is more effectual if the ends of the bar are meantime supported on the poles of other bar magnets, the poles being of the same names as those of the two magnets above them used for stroking the steel bar.

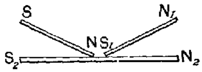


Fig. 61.

102. Magnetization by Double Touch.—Another method, known as *double touch*, differs slightly from that last described. A piece of wood or cork is interposed between the ends of the two bar magnets employed, and they are then both moved backwards and forwards along the bar that is to be magnetized. By none of these methods, however, can a steel bar be magnetized beyond a certain degree of intensity.

103. Forms of Magnets.—Natural magnets are usually of irregular form, though they are sometimes reduced to regular shapes by cutting or grinding. Formerly it was the fashion to mount them with soft iron cheeks or "armatures" to serve as pole-pieces.

For scientific experiments *bar magnets* of hardened steel are commonly used; but for many purposes the *horse-shoe* shape is preferred. In the horse-shoe magnet the poles are bent round so as to approach one another, the advantage here being that so both poles can attract one piece of iron. The "armature," or "keeper," as the piece of soft iron placed across the poles is named, is itself rendered a magnet by induction when placed across the poles; hence, when *both* poles magnetize it, the force with which it is attracted to the magnet is the greater.

104. Laminated Magnets.—It is found that long

*thin steel magnets are more powerful in proportion to their weight than thicker ones. Hence it was proposed by Scoresby * to construct* compound magnets, *consisting of thin laminæ of steel separately magnetized, and after-*

Fig. 62. Fig. 63.

wards bound together in bundles (Fig. 62). These laminated magnets are more powerful than simple bars of steel. Compound horse-shoe magnets are sometimes used: the plates separately magnetized are assembled as in Fig. 63.

105. Magnetization derived from the Earth.—The magnetism of the earth may be utilized where no other permanent magnet is available to magnetize a bar of steel. Gilbert states that iron bars set upright for a long time acquire magnetism from the earth. If a steel poker be held in the magnetic meridian, with the north end dipping down, and in this position be struck with a wooden mallet, it will be found to have acquired magnetic properties. All vertical iron columns in our northern latitudes are found to have their lower ends N-poles and their upper ends S-poles. In Australia and the southern hemisphere the tops of iron columns are N-poles. Wires of steel subjected to torsion, while in the magnetic meridian, are also found to be thereby magnetized.

106. Magnetization after Heating.—Gilbert discovered also that if a bar of steel be heated to redness, and cooled, either slowly or suddenly, while lying in the magnetic meridian, it acquires magnetic polarity. No

* A similar suggestion was made by Geuns of Venlo in 1768, using horse-shoe magnets. Similar magnets have been constructed in recent years by Jamin.

such property is acquired if it is cooled while lying east and west. It has been proposed to make powerful magnets by placing hot bars of steel to cool between the poles of very powerful electromagnets; and Carré produced strong magnets of iron cast in moulds lying in an intense magnetic field.

107. Magnetization by Currents of Electricity.—A current of electricity caused to circulate in a spiral wire wound around a core of iron or steel magnetizes it more powerfully than in any of the preceding operations. In the case of a soft iron core, it is only a magnet while the current continues to flow. Such a combination is termed an **Electromagnet**; it is fully described in Lesson XXXI. Fig. 64 depicts a common form of electromagnet having two coils of insulated copper wire wound upon bobbins that are placed upon the limbs of a soft iron core. The armature is also of soft iron of sufficient thickness. Steel bars may be magnetized by drawing them over the poles of such an electromagnet while the latter is excited by the circulation of the electric current. Elias of Haarlem proposed to magnetize steel bars by passing them through a wire coiled up into a compact ring of many turns, through which a strong current was sent by a voltaic battery.

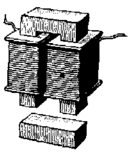


Fig. 64.

108. Hardening and Tempering of Steel for Magnets.—There are two ways of hardening steel: (1) by suddenly cooling it from a bright red temperature; (2) by compressing it under hydraulic pressure while it cools slowly. If rods of steel are heated brilliantly red, and then quenched in water, oil, or mercury, they become intensely brittle and *glass-hard*. To temper hard steel it is then gently reheated to near a very dull red heat and softens slightly while acquiring a *straw tint*. If let down still further by continuing the reheating it becomes

a *blue tint*, and is springy and flexible. Short bar magnets retain most magnetism if left glass-hard without tempering. But magnets whose length is more than twenty times their thickness retain more magnetism if tempered down to a straw or even to a blue tint.

109. Destruction of Magnetism.—A steel magnet loses its magnetism partially or wholly if subjected to rough usage, or if purposely hit or knocked about. Newly magnetized magnets lose more strength by rough treatment than those which have been long magnetized. A magnet loses its magnetism, as Gilbert showed, on being raised to a bright red heat. The slightest vibration will destroy any magnetism remaining in annealed soft iron.

110. Magnets of Unvarying Strength.—Ordinary steel magnets have by no means a permanent or constant magnetism. They soon lose a considerable percentage of their magnetism, and the decay continues slowly for months and years. Every shock or jolt to which they are subjected, every contact with iron, every change of temperature weakens them. Every time that the keeper is slammed on to a horse-shoe magnet it is weakened. For the purpose of making magnetic measurements, and for use as controlling magnets of galvanometers, magnets are, however, required that shall possess the utmost constancy in their strength. Magnets of unvarying strength may be made by attention to the following points. Choose a form either of a nearly closed circuit or of a very long rod. Let the steel be hardened as much as possible (see Art. 108 above), then placed in steam at 100° for twenty or thirty hours or more. Then magnetize as fully as possible, and then heat again for five hours in steam. Magnets of a shape constituting a nearly closed circuit are more constant than short straight magnets.

111. Effects of Heat on Magnetization.—If a permanent steel magnet be warmed by placing it in hot or boiling water, its strength will be thereby lessened, though it recovers partially on cooling. Chilling a magnet

increases its strength. Cast-iron ceases to be attracted by a magnet at a bright red heat. Pure iron is transformed at 870° C. to an almost non-magnetic state; the transformation-point of nickel is 320° C., that of cobalt 1120° C. Manganese is magnetic only when cooled to − 20° C. It has been surmised that other metals would become magnetic if cooled to a low enough temperature. Dewar observed that the magnetic susceptibility of iron, when cooled to near − 180° C. in liquid oxygen, is nearly twice as high as at 0° C. The magnetic metals at high temperatures do not become diamagnetic, but are still feebly magnetic; their susceptibility at temperatures above the transformation-point varying inversely as the absolute temperature.

112. Magnetic Saturation.—A magnet to which as powerful a degree of magnetization as it can attain to has been given is said to be *saturated*. A recently magnetized magnet will occasionally appear to be *supersaturated*, possessing even after the application of the magnetizing force has ceased a higher degree of magnetism than it is able to retain permanently. Thus a horseshoe-shaped steel magnet will support a greater weight immediately after being magnetized than it will do after its armature has been once removed from its poles. Even soft iron after being magnetized retains a small amount of magnetism when its *temporary magnetism* has disappeared. This small remaining magnetic charge is spoken of as *residual magnetism*.

113. Strength of a Magnet.—The "strength" of a magnet is not the same thing as its "lifting power." Its lifting power is a very uncertain quantity depending not only on the shape of its polar surfaces, but on the shape and quality of the mass of iron used as load. Consequently the "strength" of a magnet pole must be measured by the magnetic force which it exerts at a distance on other magnets. Thus, suppose there are two magnets, A

and B, whose strengths we compare by making them each act upon the N pole of a third magnet C. If the N pole of A repels C with twice as much force as that with which the N pole of B placed at the same distance would repel C, then we should say that the "strength" of A was twice that of B. Another way of putting the matter is to say that the "strength" of a pole is the amount of free magnetism at that pole. By adopting the unit of strength of magnet poles as defined in Art. 141, we can express the strength of any pole in numbers as so many "units" of strength.

114. Lifting Power.—The lifting power of a magnet (also called its *portative force*) depends both upon the form of the magnet and on its magnetic strength. A horse-shoe magnet will lift a load three or four times as great as a bar magnet of the same weight will lift. A long bar magnet will lift more than a short bar magnet of equal strength. A bar magnet with a rounded or chamfered end will lift more than a similar bar with a flat or expanded end, though both may be equally strongly magnetized. Also the lifting power of a magnet grows in a very curious and unexplained way by gradually increasing the load on its armature day by day until it bears a load which at the outset it could not have done. Nevertheless, if the load is so increased that the armature is torn off, the power of the magnet falls at once to its original value. The attraction between a powerful electromagnet and its armature may amount to 230 lbs. per square inch, or 16,000 grammes per square centimetre (see Art. 384). Small magnets lift a greater load in proportion to their own weight than large ones,*

* Bernoulli gave the following rule for finding the lifting power p of a magnet whose weight was w:—

$$p = a \sqrt[\frac{3}{2}]{w};$$

where a is a constant depending on the goodness of the steel and the

because the lifting power is proportional to the polar surface, other things being equal. Steel magnets seldom attain a tractive force as great as 40 lbs. per square inch of polar surface. A good steel horse-shoe magnet weighing itself 1 lb. ought to lift 25 lbs. weight. Sir Isaac Newton is *said* to have possessed a little lodestone mounted in a signet ring which would lift a piece of iron 200 times its own weight.

LESSON X.—*Distribution of Magnetism*

115. Magnetic Field.—*The space all round a magnet pervaded by the magnetic forces is termed the "field" of that magnet.* It is most intense near the poles of the magnet, and is weaker and weaker at greater distances away. At every point in a magnetic field the force has a particular strength, and acts in a particular direction. It is possible at any point in a magnetic field to draw a line in the direction of the *resultant magnetic force* acting at that point. The whole field may in this way be mapped out with magnetic lines (Art. 119). For a horse-shoe magnet the field is most intense between the two poles, and the lines of magnetic force are curves which pass from one pole to the other across the field. A practical way of investigating the distribution of the magnetic lines in a field is given in Art. 119, under the title "Magnetic Figures." When the armature is placed upon the poles of a horse-shoe magnet, the force of the magnet on all the external regions is weakened, for the induction now goes on through the iron of the keeper, not through the surrounding space. In fact a *closed system* of magnets —such as that made by placing four bar magnets along the sides of a square, the N pole of one touching the S

method of magnetizing it. In the best steel magnets made at Haarlem by Van Wetteren this coefficient was from 19·5 to 23, the weights being expressed in kilogrammes.

pole of the next—has no external field of force. A *ring* of steel may thus be magnetized so as to have neither external field nor poles; or rather any point in it may be regarded as a N pole and a S pole, so close together that they neutralize one another's forces.

That poles of opposite name do neutralize one another may be shown by the well-known experiment of hanging a small object—a steel ring or a key—to the N pole of a bar magnet. If now the S pole of another bar magnet be made to touch the first the two poles will neutralize each other's actions, and the ring or key will drop down.

116. Breaking a Magnet.—We have already stated that when a magnet is broken into two or more parts, each is a complete magnet, possessing poles, and each is nearly as strongly magnetized as the original magnet.

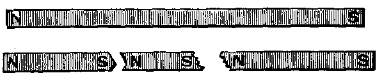


Fig. 65.

Fig. 65 shows this. If the broken parts be closely joined these adjacent poles neutralize one another and disappear, leaving only the poles at the ends as before. If a magnet be ground to powder each fragment will still act as a

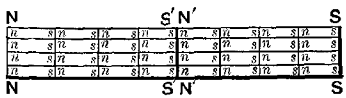


Fig. 66.

little magnet and exhibit polarity. A magnet may therefore be regarded as composed of many little magnets put together, so that their like poles all face one way. Such an arrangement is indicated in Fig. 66, from which it will be seen that if the magnet be broken asunder across

any part, one face of the fracture will present only N poles, the other only S poles. This would be true no matter how small the individual particles.

117. Normal Distribution.—In an ordinary bar magnet the poles are not quite at the ends of the bar, but a little way from it; and it can be shown that this is a result of the way in which the surface magnetism is distributed in the bar. A very long, thin, uniformly magnetized bar has its poles at the ends; but in ordinary thick magnets the "pole" occupies a considerable region, the "free magnetism" falling off gradually from the ends of the bar. In each region, however, a point can be generally determined at which the resultant magnetic forces act, and which may for most purposes be considered as the "pole." In certain cases of irregular magnetization it is possible to have one or more poles between those at the ends. Such poles are called *consequent poles* (see Fig. 70).

118. Lamellar Distribution of Magnetism. Magnetic Shells.—Up to this point the ordinary distribution of magnetism along a bar has been the only distribution considered. It is theoretically possible to have magnetism distributed over a thin sheet so that the whole of one face of the sheet shall have one kind of magnetism, and the other face the other kind of magnetism; such distribution is, however, unstable. If an immense number of little magnets were placed together side by side, like the cells in a honeycomb, all with their N-seeking ends upwards, and S-seeking ends downwards, the whole of one face of the slab would be one large flat N-seeking pole, and the other face S-seeking. Such a distribution as this over a surface or sheet is termed a **lamellar** distribution, to distinguish it from the ordinary distribution along a line or bar, which is termed, for distinction, the **solenoidal**, or **circuital**, distribution. A lamellarly magnetized magnet is sometimes spoken of as a **magnetic shell.**

119. Magnetic Figures.—Gilbert showed* that if a sheet of paper or card be placed over a magnet, and iron filings are dusted over the paper, they settle down in curving lines, forming a *magnetic figure*, the general form of which for a bar magnet is shown in Fig. 67. The filings should be fine, and sifted through a bit of muslin; to facilitate their settling in the lines, the sheet of paper should be lightly tapped. The figures thus obtained can be fixed permanently by several processes. The best of these consists in employing a sheet of glass which has

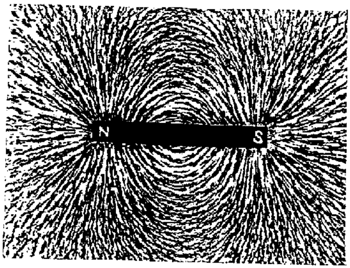


Fig. 67.

been previously gummed and dried, instead of the sheet of paper; after this has been placed above the magnet the filings are sifted evenly over the surface, and then the glass is tapped; then a jet of steam is caused to play gently above the sheet, softening the surface of the gum, which, as it hardens, fixes the filings in their places. Inspection of the figure will show that the lines diverge nearly radially from each pole, and curve round to meet these from the opposite pole. Fig. 68, produced from a horse-shoe magnet, shows how the magnetic field is most

* The magnetic figures were known to Lucretius.

intense between the poles, but spreads beyond them in wide curves. Faraday, who made a great use of this method of investigating the distribution of magnetism in various "fields," gave to the lines the name of **lines of force**. They represent, as shown by the action on little magnetic particles which set themselves thus in obedience to the attractions and repulsions in the field, the resultant direction of the forces at every point; for each particle tends to assume the direction of the force jointly due to the simultaneous action of both poles; hence the curves of filings may be taken to represent visibly the invisible *lines of magnetic force.** Faraday pointed out that these "lines of force" map out the magnetic field, showing by their position the direction of the magnetic force, and by their number its intensity. If a small N-seeking pole could be obtained alone, and put down on any one of these lines of force, it would tend to move along that line from N to S; a single S-seeking pole would

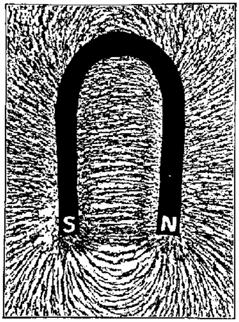


Fig. 68.

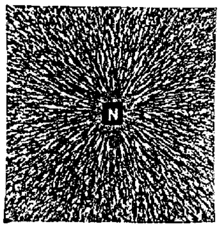


Fig. 69.

* Or rather the component part of the magnetic force resolved into the plane of the figure; which is not quite the same thing, for above the poles the filings stand up nearly vertically to this plane.

tend to move along the line in an opposite direction. In Fig. 69, which is the field about one end of a bar magnet, the magnetic lines are simply radial. Faraday also pointed out that the actions of attraction or repulsion in the field are always related to the directions in the field of the magnetic lines. He assigned to these lines of force certain physical properties (which are, however, only true of them in a secondary sense), viz. that they tend to shorten themselves from end to end, and that they repel one another as they lie side by side. The modern way of stating the matter is, that in every magnetic field there are certain stresses, consisting of a tension along the lines of force, and a pressure across them.

120. Consequent Poles.—The method of sprinkling filings may be applied to ascertain the presence of *consequent poles* in a bar of steel, the figure obtained re-

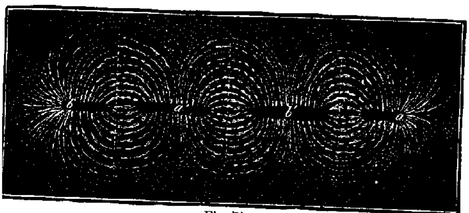


Fig. 70.

sembling that depicted in Fig. 70. Such a state of things is produced when a strip of very hard steel is purposely irregularly magnetized by touching it with strong magnets at certain points. A strip thus magnetized virtually consists of several magnets put end to end, but in reverse directions, NS, SN, etc. Consequent poles can also be produced in an electromagnet by reversing the direction in which the wire is coiled around part of the core.

121. Fields mapped by Filings.—The forces

producing attraction between unlike poles, and repulsion between like poles, are beautifully illustrated by the magnetic figures obtained in the fields between the poles in the two cases, as given in Figs. 71 and 72. In Fig. 71 the poles are of opposite kinds, and the lines of force curve across out of one pole into the other; while in

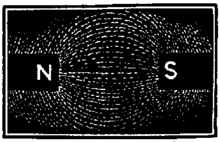


Fig. 71.

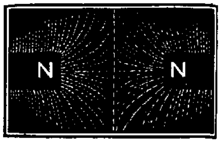


Fig. 72.

Fig. 72, which represents the action of two similar poles, the lines of force curve away as if repelling one another, and turn aside at right angles.

122. Magnetic Writing.—Another kind of magnetic figures was discovered by De Haldat, who wrote with the pole of a magnet upon a thin steel plate (such as a saw-blade), and then sprinkled filings over it. The writing, which is quite invisible in itself, comes out in the lines of filings that stick to the magnetized parts; this magic writing will continue in a steel plate many months.

123. Surface Magnetization.—In many cases the magnetism imparted to magnets is confined chiefly to the outer layers of steel. If a short bar magnet be put into acid so that the outer layers are dissolved away, it is found that it has lost its magnetism when only a thin film has been thus removed. A short hollow steel tube when magnetized is nearly as strong a magnet as a solid rod of the same size. Long thin magnets, and those that are curved so as nearly to form a closed circuit, can be much more thoroughly magnetized. If a bundle of steel plates are magnetized while bound together, it will be

found that only the outer ones are strongly magnetized. The inner ones may even exhibit a reversed magnetization.

124. Mechanical Effects of Magnetization.—Joule found an iron bar to increase by $\frac{1}{720000}$ of its length when strongly magnetized. Bidwell found that with still stronger magnetizing forces iron contracts again; and rods stretched by a weight contract more when magnetized than unstretched rods do. Barrett observed that nickel shows a slight contraction when magnetized. These are proofs that magnetization is an action affecting the arrangement of the molecules. This supposition is confirmed by the observation of Page, that at the moment when a bar is magnetized or demagnetized, a faint metallic clink is heard in the bar. Sir W. Grove showed that when a tube containing water rendered muddy by stirring up in it finely-divided magnetic oxide of iron was magnetized, the liquid became clearer in the direction of magnetization, the particles apparently setting themselves end-on, and allowing more light to pass between them. A twisted iron wire tends to untwist itself when magnetized. A piece of iron, when powerfully magnetized and demagnetized in rapid succession, grows hot, as if magnetization were accompanied by internal friction.

125. Action of Magnetism on Light.—Faraday discovered that a ray of polarized light passing through certain substances in a powerful magnetic field has the direction of its vibrations changed. This phenomenon, which is sometimes called "The Magnetization of Light," is better described as "The Rotation of the Plane of Polarization of Light by Magnetism." The amount of rotation differs in different media, and varies with the magnetizing force. More recently Kerr has shown that a ray of polarized light is also rotated by reflexion at the end or side of a powerful magnet. Further mention is made of these discoveries in the chapter on Electro-optics, Lesson LVI.

126. The Act of Magnetizing.—All these various

phenomena point to a theory of magnetism very different from the old notion of fluids. It appears that every particle of a magnet is itself a magnet, and that the magnet only becomes a magnet as a whole by the particles being so turned as to point one way. The act of magnetizing consists in turning the molecules more or less into one particular direction. This conclusion is supported by the observation that if a glass tube full of iron filings is magnetized, the filings can be seen to set themselves endways, and that, when thus once set, they act as a magnet until shaken up. It appears to be harder to turn the individual molecules of solid steel than those of soft iron; but, when once so set, they remain end-on unless violently struck or heated. As Weber, who propounded this notion of molecular magnetism, pointed out, it follows from this theory that when all the particles are turned end-on the limits of possible magnetization would have been attained. Some careful experiments of Beetz on iron deposited by electrolysis entirely confirm this conclusion, and add weight to the theory. Fig. 73 may be taken to represent a non-magnetized piece of iron or steel in which the arrangement of the particles is absolutely miscellaneous: they do not point in any one direction more than another. When magnetized slightly, there will be a greater percentage pointing in the direction of the magnetizing force. When fully magnetized—if that were possible—they would all point in the same direction as in Fig. 74.

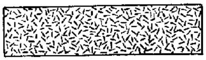


Fig. 73.

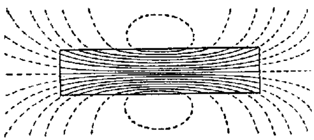


Fig. 74.

In very few cases, however, is the magnetization uniform throughout the whole length of a bar: the particles are more fully completely turned into line at the middle part of the bar than at the ends.

If the intrinsic magnetization of the steel at every part of a magnet were equal, the free poles would be found only at the end surfaces; but the fact that the free magnetism is not at the ends merely, but diminishes from the ends towards the middle, shows that the intensity of the intrinsic magnetization must be less towards and at the ends than it is at the middle of the bar. In Fig. 74 an attempt is made to depict this. It will be noticed that the magnetic lines run through the steel and emerge into the air in curves. Some of the lines do not run all the length of the bar but leak out at the sides. If the bar were uniformly magnetized the lines would emerge at the ends only. It is clear that the middle piece is more thoroughly magnetized than any other part. Magnetism in fact consists of a sort of grain or structure conferred upon the steel. Wherever this structure comes up at a surface, there the surface properties of magnetism are found. A pole is simply a region where the magnetic lines pass through the surface of the steel or iron.

The optical phenomena led Clerk Maxwell to the further conclusion that these longitudinally-set molecules are rotating round their long axes, and that in the "ether" of space there is also a vortical motion along the lines of magnetic induction; this motion, if occurring in a perfect medium (as the "ether" may be considered), producing tensions along the lines of the magnetic field, and pressures at right angles to them, would afford a satisfactory explanation of the magnetic attractions and repulsions which apparently act across empty space.

Hughes, Barus, and others have lately shown that the magnetism of iron and steel is intimately connected with the molecular rigidity of the material. Hughes's researches with the "induction balance" (Art. 514) and

"magnetic balance" (Art. 140) tended to prove that each molecule of a magnetic metal has an absolutely constant inherent magnetic polarity; and that when a piece of iron or steel is apparently neutral, its molecules are internally arranged so as to satisfy each other's polarity, forming closed magnetic circuits amongst themselves.

127. Ewing's Theory of Molecular Magnetism.—Weber supposed that there was in hard steel some sort of friction which prevented the molecules when once magnetized from turning back into higgledy-piggledy positions. Ewing, however, showed that a complete explanation was afforded by supposing the particles to be subject to mutual forces. In any group not subjected to an external magnetizing force the particles will arrange themselves so as to satisfy one another's polarity. Of the

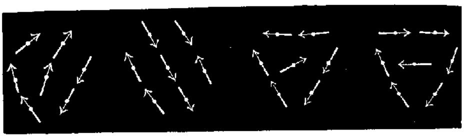


Fig. 75.

possible groupings some are, however, unstable. Four possible stable groupings of seven pivoted needles are shown in Fig. 75. Ewing constructed a model consisting of a large number of pivoted magnetic needles arranged in one layer. When these needles were simply agitated and allowed to come to rest they settled down in miscellaneous groups; but when acted upon by a gradually increasing magnetic force they turned round, the operation showing three stages—(i.) with very small magnetizing force the needles merely turned through a small angle; (ii.) when a certain force was applied the groupings became unstable, some of the needles suddenly swinging round to a new position, with the result that the majority of the needles

point nearly but not quite along the direction of the force; (iii.) a further increase of the magnetizing force cannot produce much more effect; it can only pull the needles a little more perfectly into line. All these things correspond to the three stages observed (see Art. 364) in the gradual magnetization of iron or steel.

LESSON XI.—*Laws of Magnetic Force*

128. Laws of Magnetic Force.

FIRST LAW.—*Like magnetic poles repel one another; unlike magnetic poles attract one another.*

SECOND LAW.—*The force exerted between two magnetic poles is proportional to the product of their strengths, and is inversely proportional to the square of the distance between them, provided that the distance is so great that the poles may be regarded as mere points.*

129. The Law of Inverse Squares.—The second of the above laws is commonly known as the law of *inverse squares;* it is essentially a law of point-action, and is not true for poles of elongated or extended surface. The similar law of electrical attraction has already been explained and illustrated (Art. 19). This law furnishes the explanation of a fact mentioned in an earlier lesson, Art. 91, that small pieces of iron are drawn bodily up to a magnet pole. If a small piece of iron wire, a, b (Fig 76), be suspended by a thread, and the N-pointing pole

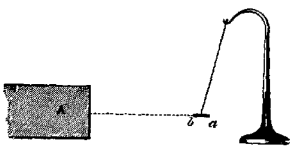


Fig. 76.

A of a magnet be brought near it, the iron is thereby inductively magnetized; it turns round and points towards the magnet pole, setting itself as nearly as possible along a line of force, its near end *b* becoming a S-seeking pole, and its farther end *a* becoming a N-seeking pole. Now the pole *b* will be attracted and the pole *a* will be repelled. But these two forces do not exactly equal one another, since the distances are unequal. The repulsion will (by the law of inverse squares) be proportional to $\frac{1}{(\mathrm{A}a)^2}$; and the attraction will be proportional to $\frac{1}{(\mathrm{A}b)^2}$. Hence the bit of iron *a*, *b* will experience a pair of forces, turning it into a certain direction, and also a total force drawing it bodily toward A. Only those bodies are attracted by magnets in which magnetism can thus be induced; and they are attracted only because of the magnetism induced in them.

We mentioned, Art. 91, that a magnet needle floating freely on a bit of cork on the surface of a liquid is acted upon by forces that give it a certain direction, but that, unlike the last case, it does not tend to rush as a whole either to the north or to the south. It experiences a rotation, because the attraction and repulsion of the magnetic poles of the earth act in a certain direction; but since the magnetic poles of the earth are at a distance enormously great as compared with the length from one pole of the floating magnet to the other, we may say that, for all practical purposes, the poles of the magnet are at the same distance from the N pole of the earth. The attracting force on the N-pointing pole of the needle is therefore practically no greater than the repelling force acting on the S-pointing pole, hence there is no motion of translation given to the floating needle as a whole: it is *directed*, not *attracted*.

130. Measurement of Magnetic Forces.—The truth of the law of inverse squares can be demonstrated by experiment. But this implies that we have some

means of measuring accurately the amount of the magnetic forces of attraction or repulsion. Magnetic force may be measured in any one of the four following ways: (1) by observing the time of swing of a magnetic needle oscillating under the influence of the force; (2) by observing the deflexion it produces upon a magnetic needle which is already attracted into a different direction by a force of known intensity; (3) by balancing it against the torsion of an elastic thread; (4) by balancing it against the force of gravity as brought into play in attempting to deflect a magnet hung by two parallel strings (called the *bifilar* suspension), for these strings cannot be twisted out of their parallel position without raising the centre of gravity of the magnet.

131. Deflexion Experiment.—Fig. 77 shows an apparatus in which a compass-needle can be deflected by one pole of a magnet made of a long thin bar of steel, so mounted that its upper pole is always over the centre of the needle, and therefore has no tendency to turn it. So set, it acts as a one-pole magnet, the pole of which can be placed at different distances from the compass-needle. It is found, using a proper tangent-scale (see Art. 211) for the compass-needle, that when the distance is doubled the deflecting force is reduced to one quarter, and so forth.

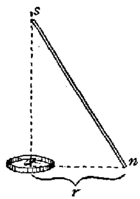


Fig. 77.

132. The Torsion Balance.—Coulomb applied the Torsion Balance to the measurement of magnetic forces. The main principles of this instrument (as used to measure forces of electrostatic repulsion) were described on p. 20. Fig. 78 shows how it is arranged for measuring magnetic repulsions.

To prove the law of inverse squares, Coulomb made the following experiment:—The instrument was first adjusted

so that a magnetic needle, hung in a copper stirrup to the fine silver thread, lay in the magnetic meridian without the wire being twisted. This was done by first putting in the magnet and adjusting roughly, then replacing it by a copper bar of equal weight, and once more adjusting, thus diminishing the error by repeated trials. The next

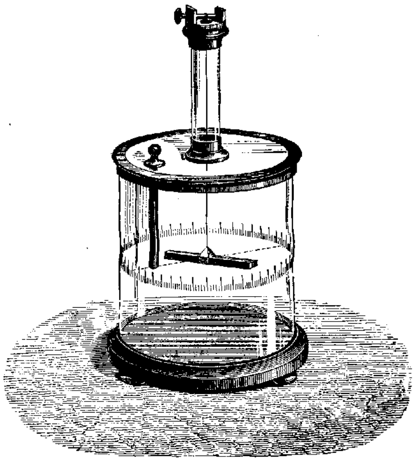


Fig. 78.

step was to ascertain through what number of degrees the torsion-head at the top of the thread must be twisted in order to drag the needle 1° out of the magnetic meridian. In the particular experiment cited it was found that 35° of torsion corresponded to the 1° of deviation of the magnet; then a magnet was introduced through the lid, that pole being downwards which repelled the pole of the

suspended needle. It was found (in this particular experiment) to repel the pole of the needle through 24°. From the preliminary trial we know that this directive force corresponds to $24° \times 35°$ of the torsion-head, and to this we must add the actual torsion on the wire, viz. the 24°, making a total of 864°, which we will call the "torsion equivalent" of the repelling force when the poles are thus 24° apart. Finally, the torsion-head was turned round so as to twist the suspended magnet round, and force it nearer to the fixed pole, until the distance between the repelling poles was reduced to half what it was at first. It was found that the torsion-head had to be turned round 8 complete rotations to bring the poles to 12° apart. These 8 rotations were an actual twist of $8° \times 360°$, or 2880°. But the bottom of the torsion thread was still twisted 12° as compared with the top, the force producing this twist corresponding to 12×35 (or 420°) of torsion; and to these the actual torsion of 12° must be added, making a *total* of $2880° + 420° + 12° = 3312$. The result then of halving the distance between the magnet poles was to increase the force *fourfold*, for 3312 is very nearly four times 864. Had the distance between the poles been reduced to one-third the force would have been nine times as great.

We may also, assuming this law proved, employ the balance to measure the strengths of magnet poles by measuring the forces they exert at known distances.

133. Method of Oscillations.*—If a magnet suspended by a fine thread, or poised upon a point, be pushed aside from its position of rest, it will vibrate backwards and forwards, performing oscillations which, although they gradually decrease in amplitude, are executed in *very*

* It is possible, also, to measure *electrical* forces by a "method of oscillations"; a small charged ball at the end of a horizontally-suspended arm being caused to oscillate under the attracting force of a charged conductor near it, whose "force" at that distance is proportional to the square of the number of oscillations in a given time.

nearly equal times. In fact, they follow a law similar to that of the oscillations executed by a pendulum swinging under the influence of gravity. The law of pendular vibrations is, that *the square of the number of oscillations executed in a given time is proportional to the force.* Hence we can measure magnetic forces by counting the oscillations made in a minute by a magnet. It must be remembered, however, that the actual number of oscillations made by any given magnet will depend on the weight of the magnet and on its leverage around its centre, as well as upon the strength of its poles, and on the intensity of the field in which it may be placed (see calculations, Art. 361).

We can use this method to compare the intensity of the force of the earth's magnetism * at any place with that at any other place on the earth's surface, by oscillating a magnet at one place and then taking it to the other place and oscillating it there. If, at the first, it makes a oscillations in one minute, and at the second b oscillations a minute, then the magnetic forces at the two places will be to one another in the ratio of a^2 to b^2.

Again, we may use the method to compare the force exerted at any point by a magnet near it with the force of the earth's magnetism at that point. For, if we swing a small magnetic needle there, and find that it makes m oscillations a minute under the joint action † of the earth's magnetism, and that of the neighbouring magnet, and that, when the magnet is removed, it makes n oscillations a minute under the influence of the earth's magnetism alone, then m^2 will be proportional to the joint forces, n^2 to the force due to the earth's magnetism, and the difference of these, or $m^2 - n^2$ will be proportional to the force due to the neighbouring magnet.

* Or, more strictly, of its *horizontal component*.

† We are here assuming that the magnet is so placed that its force is in a line with that of the earth's magnetism at the point, and that the other pole of the magnet is so far away as not to affect the oscillating needle.

134. Surface Distribution.—We will now apply the method of oscillations to measure the relative quantities of surface magnetism at different points along a bar magnet. The magnet to be examined is set up vertically (Fig. 79). A small magnet, capable of swinging horizontally, is brought near it and set at a short distance away from its extremity, and then oscillated, while the rate of its oscillations is counted. Suppose the needle were such that, when exposed to the earth's magnetism alone, it would perform 3 complete oscillations a minute, and that, when vibrating at its place near the end of the vertical magnet it oscillated 14 times a minute, then the force due to the magnet will be proportional to $14^2 - 3^2 = 196 - 9 = 187$. Nextly, let the oscillating magnet be brought to an equal distance opposite a point a little away from the end of the vertical magnet. If, here, it oscillated 12 times a minute, we know that the force will be proportional to $12^2 - 3^2 = 144 - 9 = 135$. So we shall find that as the force falls off the oscillations will be fewer, until, when we put the oscillating magnet opposite the middle of the vertical magnet, we shall find that the number of oscillations is 3 per minute, or that the earth's force is the only force affecting the oscillations. In Fig. 80 we have indicated the number of oscillations at successive points, as 14, 12, 10, 8, 6, 5, 4, and 3. If we square these numbers and subtract 9 from each, we shall get for the forces at the various points the following:—187, 135, 91, 55, 27, 16, 7, and 0. These forces may be taken to represent the strength of the free magnetism at the various points, and it is convenient to plot them out graphically in the manner shown in Fig. 80, where the heights of the dotted lines are chosen to a scale to represent proportionally the forces. The curve which

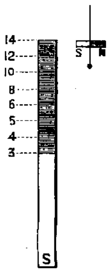


Fig. 79.

joins the tops of these ordinates shows graphically how the force, which is greatest at the end, falls off toward the middle. On a distant magnet pole these forces, thus represented by this curvilinear triangle, would act as if

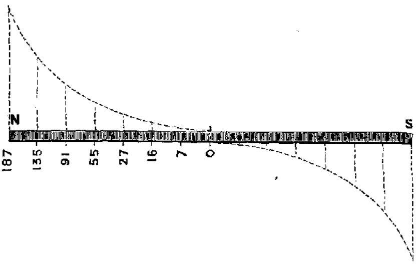


Fig. 80.

concentrated at a point in the magnet opposite the "centre of gravity" of this triangle; or, in other words, the "pole," which is the centre of the resultant forces, is not at the end of the magnet. In thin bars of magnetized steel it is at about $\frac{1}{10}$ of the magnet's length from the end.

135. Magnetic Moment.—It is found that the tendency of a magnet to turn or to be turned by another magnet depends not only on the *strength* m of its poles, but the *length* l between them. The product of these two quantities $m \times l$ is called the **magnetic moment** of the magnet, and is sometimes denoted by the symbol M. As the exact position of a magnet's poles are often unknown, it is easier to determine M than to measure either m or l separately.

136. Method of Deflexions.—There are a number of ways in which the deflexion of a magnet by another magnet may be made use of to measure magnetic forces.*

* The student desirous of mastering these methods of measuring magnetic forces should consult Professor Andrew Gray's *Absolute Measurements in Electricity and Magnetism.*

We cannot here give more than a glance at first principles. When two equal and opposite forces act on the ends of a rigid bar they simply tend to turn it round. Such a pair of forces form what is called a "couple," and the *torque*, or tendency to turn (formerly called the "moment" of the couple), is obtained by multiplying one of the two forces by the perpendicular distance between the directions of the forces. Such a couple tends to produce a motion of rotation, but not a motion of translation. Now a magnetic needle placed in a magnetic field across the lines of force experiences a torque, tending to rotate it round into the magnetic meridian, for the N-seeking pole is urged northwards, and the S-seeking pole is urged southwards, with an equal and opposite force. The force acting on each pole is the product of the strength of the pole and the intensity of the "field," that is to say, of the horizontal component of the force of the earth's magnetism at the place. We will call the strength of the N-seeking pole m; and we will use the symbol H to represent the force which the earth's magnetism would exert in a horizontal direction on a unit of magnetism. (The value of H is different at different regions of the globe.) The force on the pole A (see Fig. 81) will be then $m \times \mathrm{H}$, and that on pole B will be equal and opposite. We take NS as the direction of the magnetic meridian: the forces will be parallel to this direction. Now, the needle AB lies

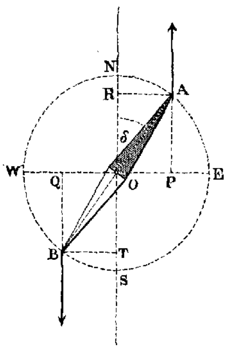


Fig. 81.

obliquely in the field, while the magnetic force acting on A is in the direction of the line PA, and that on B in the direction QB, as shown by the arrows. PQ is the perpendicular distance between these forces; hence the "moment" of the couple, or torque, will be got by multiplying the length PQ by the force exerted on one of the poles. Using the symbol Y for the torque, we may write

$$Y = PQ \times m \cdot H.$$

But PQ is equal to the length of the magnet multiplied by the sine * of the angle AOR, which is the angle of deflexion, and which we will call δ. Hence, using l for the length between the poles of the magnet, we may write the expression for the moment of the couple.

$$Y = mlH \cdot \sin \delta.$$

In words this is: the torque acting on the needle is proportional to its "magnetic moment" $(m \times l)$, to the horizontal force of the earth's magnetism, and to the sine of the angle of deflexion.

The reader will not have failed to notice that if the needle were turned more obliquely, the distance PQ would be longer, and would be greatest if the needle were turned round east-and-west, or in the direction EW. Also the torque tending to rotate the magnet will be less and less as the needle is turned more nearly into the direction NS.

137. Law of Tangents.—Now, let us suppose that the deflexion δ were produced by a magnetic force applied at right angles to the magnetic meridian, and tending to draw the pole A in the direction RA. The length of the line RT multiplied by the new force will be the leverage of the new couple tending to twist the magnet into the direction

* If any reader is unacquainted with trigonometrical terms he should consult the note at the end of this lesson, on "Ways of Reckoning Angles."

EW. Now, if the needle has come to rest in equilibrium between these two forces, it is clear that the two opposing twists are just equal and opposite in power, or that the torque due to one couple is equal to that of the other couple. Hence the force in the direction WE will be to the force in the direction SN in the same ratio as PQ is to RT, or as PO is to RO.

Or, calling this force f,

$$f : \mathrm{H} = \mathrm{PO} : \mathrm{RO}.$$

Or $$f = \mathrm{H}\frac{\mathrm{PO}}{\mathrm{RO}}.$$

But $\mathrm{PO} = \mathrm{AR}$ and $\frac{\mathrm{AR}}{\mathrm{RO}} = \tan\delta$, hence

$$f = \mathrm{H}\tan\delta\,;$$

or, in other words, *the magnetic force which, acting at right angles to the meridian, produces on a magnetic needle the deflexion* δ, *is equal to the horizontal force of the earth's magnetism at that point, multiplied by the tangent of the angle of deflexion.* Hence, also, two different magnetic forces acting at right angles to the meridian would severally deflect the needle through *angles whose tangents are proportional to the forces.*

This very important theorem is applied in the construction of certain galvanometers (see Art. 212).

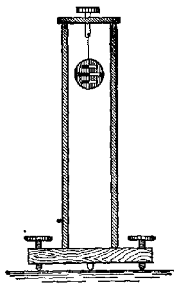


Fig. 82.

138. Magnetometers.— The name **Magnetometer** is given to any magnet specially arranged as an instrument for the purpose of measuring magnetic forces. The methods of observing the *absolute* values of magnetic forces in *dyne-units* (units in the "C.G.S." system) will be explained in Art. 361

at the end of Lesson XXVII. Very simple magnetometers, consisting of small needles pivoted, or suspended by a fibre, are commonly used for measuring the *relative* values of magnetic forces. One very sensitive form (Fig. 82), to be used, like the reflecting galvanometer (Art. 215), with a beam of light as a pointer, consists of a small thin silvered glass mirror, a half-inch or less in diameter, having two or three very light magnets cemented at its back, suspended by a single thread of cocoon silk, and enclosed in a suitable case.

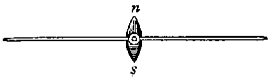


Fig. 83.

Another useful form (Fig. 83) consists of a short compass-needle poised on a pivot having a light index of aluminium long enough to move over a scale divided into tangent values (see Art. 212).

A convenient deflexion magnetometer for comparing the magnetic moments (Art. 135) of two magnets is

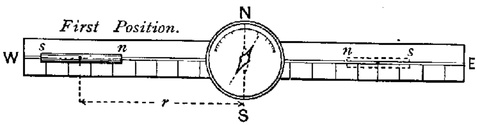


Fig. 84.

afforded by such a tangent compass placed in the middle of a graduated platform (Fig. 84). There are two methods of using this apparatus.

First Position: End-on Method.—The platform being set magnetically east and west, the deflecting magnet is set *end-on.* Under these circumstances the force is found to vary directly as the magnetic moment (Art. 135), and *inversely as the cube* of the distance between the centres of the magnets, or in symbols :—

$$f = 2M/r^3.$$

But we have seen above that where magnetic force is measured by a deflexion δ at a place where the H is earth's horizontal magnetic force, f is equal to H tan δ; so that

$$2M/r^3 = H \tan \delta,$$

whence

$$M = \tfrac{1}{2} r^3 H \tan \delta.$$

Second Position: Broadside-on.—The platform being turned into the north-south position, the deflecting magnet is set *broadside-on.* In this case the magnet deflects the needle in the other direction and with half the force that it would have exerted at an equal distance in the end-on position. But the force still varies *inversely as the cube* of the distance: the formula being now

$$f = M/r^3,$$

whence

$$M = r^3 H \tan \delta.$$

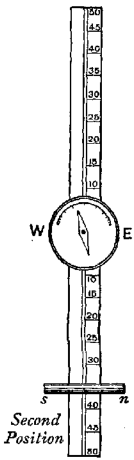


Fig. 85.

139. Balance Methods.—In either position of the magnetometer platform two magnets can be placed on the two sides of the board so as to balance one another's effects by adjusting them to proper distances. This gives a comparison of their magnetic moments in terms of their respective distances, or

$$M_1 : M_2 = r_1^3 : r_2^3.$$

140. Hughes's Magnetic Balance.—A very convenient instrument for testing the magnetic properties of different specimens of iron and steel was devised by Hughes in 1884. The sample to be tested

is placed in a magnetizing coil A (Fig. 86), and a current is sent round it. It deflects a lightly-suspended indicating needle B, which is then brought to zero by turning a large compensating magnet M upon its centre. A small coil C is added to balance the direct deflecting effect due

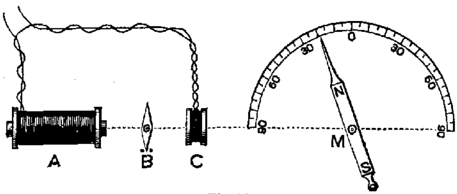


Fig. 86.

to coil A. The author of this book has shown that if the distance from M to B is 2·3 times the length of M, the angle through which M is turned is proportional to the magnetic force due to the iron core at A, provided the angle is less than 60°.

141. Unit Strength of Pole.—The Second Law of Magnetic Force (see Art. 128) stated that the force exerted between two poles was proportional to the product of their strengths, and was inversely proportional to the square of the distance between them. It is possible to choose such a strength of pole that this proportionality shall become numerically an equality. In order that this may be so, we must adopt the following as our unit of strength of a pole, or unit magnetic pole: *A Unit Magnetic Pole is one of such a strength that, when placed at a distance of one centimetre from a similar pole of equal strength it repels it with a force of one dyne* (see Art. 352). If we adopt this definition we may express the second law of magnetic force in the following equation:—

$$f = \frac{m \times m'}{d^2},$$

where f is the force (in dynes), m and m' the strengths of the two poles, and d the distance between them (in centimetres). From this definition is derived the arbitrary convention about magnetic lines. If at any place in a magnetic field we imagine a unit magnetic pole to be set it will be acted upon, tending to move along the lines of the field. Then if at that place we find the force on the pole to be H dynes, we may conceive that there are H lines drawn per square centimetre. For example, if we describe the field as having 50 lines side by side per square centimetre, we mean that a unit pole placed there will be acted on with a force of 50 dynes. Or we may say simply: the intensity of the field is 50 *gausses* (see Art. 338).

142. Theory of Magnetic Curves.—We saw (Art. 119) that magnetic figures are produced by iron filings setting themselves in certain directions in the field of force around a magnet. We can now apply the law of inverse squares to aid us in determining the direction in which a filing will set itself at any point in the field. Let NS (Fig. 87) be a long thin magnet, and P any point in the field due to its magnetism. If the N-seeking pole of a small magnet be put at P, it will be attracted by S and repelled by N; the directions of these two forces will be along the lines PS and PN. The amounts of the forces may be represented by certain lengths marked out along these lines. Suppose the distance PN is twice as great as PS, the repelling force along PN will be $\frac{1}{4}$ as strong as the attracting force along PS. So measure a distance out, PA towards S four times as long as the length PB measured along PN away from N. Find the resultant force in the usual way of compounding mechanical forces, by completing the parallelogram PARB; the diagonal PR represents by its length and direction the magnitude and the direction of the resultant magnetic force at the point P. In fact the line PR represents the line along which a small magnet or an

iron filing would set itself. In a similar way we might ascertain the direction of the lines of force at any point of the field. The little arrows in Fig. 87 show how the lines of force start out from the N pole and curve round to meet in the S pole. The student should compare this

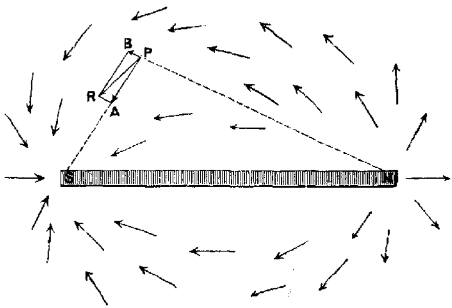


Fig. 87.

figure with the lines of filings of Fig. 67. Henceforth we must think of every magnet as being permeated by these magnetic lines which extend out into the surrounding space. The whole number of magnetic lines which run through a magnet is termed its *magnetic flux* (Art. 337).

143. A Magnetic Paradox.—If the N-seeking pole of a strong magnet be held at some distance from the N-seeking pole of a weak magnet, it will repel it; but if it is pushed up quite close it will be found now to *attract* it. This paradoxical experiment is explained by the fact that the magnetism induced in the weak magnet by the powerful one will be of the opposite kind, and will be attracted; and, when the powerful magnet is near, this induced magnetism may overpower and mask the original magnetism of the weak magnet. The

student must be cautioned that in most of the experiments on magnet poles similar perturbing causes are at work. The magnetism in a magnet is not quite *fixed*, but is liable to be disturbed in its distribution by the near presence of other magnet poles, for no steel is so hard as not to be temporarily affected by magnetic induction.

NOTE ON WAYS OF RECKONING ANGLES AND SOLID ANGLES

144. Reckoning in Degrees.—When two straight lines cross one another they form an *angle* between them; and this angle may be defined as the amount of rotation which one of the lines has performed round a fixed point in the other line. Thus we may suppose the line CP in Fig. 88 to have originally lain along CO, and then turned round to its present position. The amount by which it has been rotated is clearly a certain fraction of the whole way round; and the amount of rotation round C we call "the angle which PC makes with OC," or more simply "the angle PCO." But there are a number of different ways of *reckoning* this angle. The common way is to reckon the angle by "degrees" of arc. Thus, suppose a circle to be drawn round C, if the circumference of the circle were divided into 360 parts each part would be called "one degree" (1°), and the angle would be reckoned by naming the number of such degrees along the curved arc OP. In the figure the arc is about $57\frac{1}{4}°$, or $\frac{57\frac{1}{4}}{360}$ of the whole way round, no matter what size the circle is drawn.

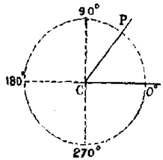


Fig. 88.

145. Reckoning in Radians.—A more sensible but less usual way to express an angle is to reckon it by the ratio between the length of the curved arc that "subtends" the angle and the length of the radius of the circle. Suppose we have drawn round the centre C a circle whose *radius* is *one* centimetre, the *diameter* will be *two* centimetres. The length of the circumference all round is known to be about $3\frac{1}{7}$ times the length of the diameter, or more exactly 3·14159 . . . This number is so awkward

that, for convenience, we always use for it the Greek letter π. Hence the length of the circumference of our circle, whose radius is one centimetre, will be 6·28318 . . . centimetres, or 2π centimetres. We can then reckon any angle by naming the length of arc that subtends it on a circle one centimetre in radius. If we choose the angle PCO, such that the curved arc OP shall be just one centimetre long, this will be the angle *one*, or unit of angular measure, or, as it is sometimes called, the angle PCO will be *one "radian."* In degree-measure one radian $= \frac{360°}{2\pi} = 57° \ 17'$ nearly. All the way round the circle will be 2π radians. A right angle will be $\frac{\pi}{2}$ radians.

146. Reckoning by Sines or Cosines.—In trigonometry other ways of reckoning angles are used, in which, however, the angles themselves are not reckoned, but certain "functions" of them called "sines," "cosines," "tangents," etc. For readers not accustomed to these we will briefly explain the geometrical nature of these "functions." Suppose we draw (Fig. 89) our circle as before round centre C, and then drop down a plumb-line PM, on to the line CO; we will, instead of reckoning the angle by the curved arc, reckon it by the length of the line PM. It is clear that if the angle is small PM will be short; but as the angle opens out towards a right angle, PM will get longer and longer (Fig. 90). The ratio between the length of this line and the radius of the circle is called the "*sine*" *of the angle*, and if the radius is 1 the length of PM will be the value of the sine. It can never be greater than 1, though it may have all values between 1 and -1. The length of the line CM will also depend upon the amount of the angle. If the angle is small CM will be nearly as long as CO; if the angle open out to nearly a right angle CM will be very short. The length of CM (when the radius is 1) is called *the "cosine" of the angle.* If the angle be called θ, then we may for shortness write these functions:

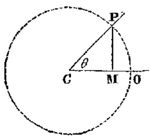


Fig. 89.

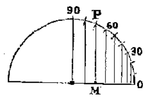


Fig. 90.

$$\text{Sin } \theta = \frac{PM}{CP}$$

$$\text{Cos } \theta = \frac{CM}{CP}.$$

147. Reckoning by Tangents.—Suppose we draw our circle as before (Fig. 91), but at the point O draw a straight line touching the circle, the *tangent line* at O; let us also prolong CP until it meets the tangent line at T. We may measure the angle between OC and OP in terms of the length of the tangent OT as compared with the length of the radius. Since our radius is 1, this ratio is numerically the length of OT, and we may therefore call the length of OT *the "tangent" of the angle* OCP. It is clear that smaller angles will have smaller tangents, but that larger angles may have very large tangents; in fact, the length of the tangent when PC was moved round to a right angle would be infinitely great. It can be shown that the ratio between the lengths of the sine and of the cosine of the angle is the same as the ratio between the length of the tangent and that of the radius; or the tangent of an angle is equal to its sine divided by its cosine. The formula for the tangent may be written:

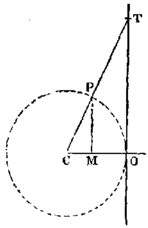


Fig. 91.

$$\tan \theta = \frac{\mathrm{TO}}{\mathrm{OC}} = \frac{\mathrm{PM}}{\mathrm{MC}}.$$

148. Solid Angles.—When three or more surfaces intersect at a point they form a *solid angle*: there is a solid angle, for example, at the top of a pyramid, or of a cone, and one at every corner of a diamond that has been cut. If a surface of any given shape be near a point, it is said to subtend a certain solid angle at that point, the solid angle being mapped out by drawing lines from all points of the edge of this surface to the point P (Fig. 92). An irregular cone will thus be generated whose solid angle is the solid angle subtended at P by the surface EF. To reckon this solid angle we adopt an expedient similar to that adopted when we wished to reckon a plane angle in radians. About the point P, with radius of 1 centimetre, describe a *sphere*, which will intercept

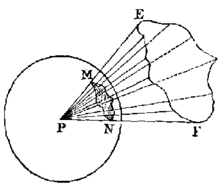


Fig. 92.

the cone over an area MN : the area thus intercepted measures the solid angle. If the sphere have the radius 1, its total surface is 4π. The solid angle subtended at the centre by a hemisphere would be 2π. It will be seen that the ratio between the area of the surface EF and the area of the surface MN is the ratio between the squares of the lines EP and MP. The solid angle subtended by a surface at a point (other things being equal) is inversely proportional to the square of its distance from the point. This is the basis of the law of inverse squares.

A table of radians, sines, tangents, etc., is given at the end of this book as Appendix A.

Lesson XII.—*Terrestrial Magnetism*

149. The Mariner's Compass.—It was mentioned in Art. 87 that the compass sold by opticians consists of

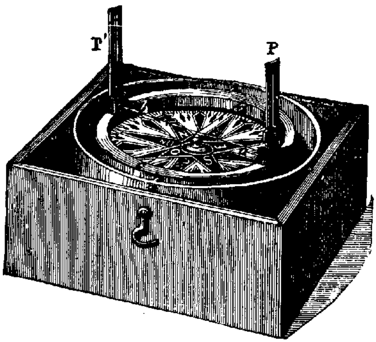


Fig. 93.

a magnetized steel needle balanced on a fine point above a card marked out N, S, E, W, etc. The **Mariner's Compass** is, however, somewhat differently arranged.

In Fig. 93 one of the forms of a Mariner's Compass,

used for nautical observations, is shown. Here the card, divided out into the 32 "points of the compass," is itself attached to the needle, and swings round with it so that the point marked N *on the card* always points to the north. In the best modern ships' compasses, such as those of Lord Kelvin, several magnetized needles are placed side by side, as it is found that the indications of such a compound needle are more reliable. The iron fittings of wooden vessels, and, in the case of iron vessels, the ships themselves, affect the compass, which has therefore to be corrected by placing compensating masses of iron near it, or by fixing it high upon a mast. The error of the compass due to magnetism of the ship is known as the *deviation*.

150. The Earth a Magnet.—Gilbert made the great discovery that the compass-needle points north and south because the earth is itself also a great magnet. The magnetic poles of the earth are, however, not exactly at the geographical north and south poles. The magnetic north pole of the earth is more than 1000 miles away from the actual pole, being in lat. 70° 5′ N., and long. 96° 46′ W. In 1831 it was found by Sir J. C. Ross to be situated in Boothia Felix, just within the Arctic Circle. The south magnetic pole of the earth has never been reached; and by reason of irregularities in the distribution of the magnetism there appear to be two south magnetic polar regions.

151. Declination.—In consequence of this natural distribution the compass-needle does not at all points of the earth's surface point truly north and south. Thus, in 1894, the compass-needle at London pointed at an angle of about 17° west of the true north; in 1900 it was 16° 16′. This angle between the *magnetic meridian* * and

* The *Magnetic Meridian* of any place is an imaginary plane drawn through the zenith, and passing through the magnetic north point and magnetic south point of the horizon, as observed at that place by the pointing of a horizontally-suspended compass-needle.

the geographical meridian of a place is called the magnetic **Declination** of that place. The existence of this declination was discovered by Columbus in 1492, though it appears to have been previously known to the Chinese, and is said to have been noticed in Europe in the early part of the thirteenth century by Peter Peregrinus. The fact that the declination differs at different points of the earth's surface, is the undisputed discovery of Columbus.

In order that ships may steer by the compass, magnetic charts (Art. 154) must be prepared, and the declination at different places accurately measured. The upright pieces P, P′, on the "azimuth compass" drawn in Fig. 93, are for the purpose of sighting a star whose position may be known from astronomical tables, and thus affording a comparison between the magnetic meridian of the place and the geographical meridian, and of measuring the angle between them.

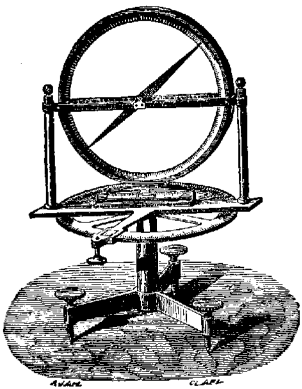


Fig. 94.

152. Inclination or Dip.—Norman, an instrument-maker, discovered in 1576 that a balanced needle, when magnetized, tends to dip downwards toward the north. He therefore constructed a **Dipping-Needle**, capable of turning in a vertical plane about a horizontal axis, with which he found the "dip" to be (at London) an

angle of 71° 50′. A simple form of Dipping-needle is shown in Fig. 94. The dip-circles used in the magnetic observatory at Kew are much more exact and delicate instruments. It was, however, found that the dip, like the declination, differs at different parts of the earth's surface, and that it also undergoes changes from year to year. The "dip" in London for the year 1894 is 67° 18′; in 1900 it was 67° 9′. At the north magnetic pole the needle dips straight down. The following table gives particulars of the Declination, Inclination, and total magnetic force at a number of important places, the values being approximately true for the year 1900.

TABLE OF MAGNETIC DECLINATION AND INCLINATION (for Year 1900)

Locality.	Declination.	Dip.	Total Force (C.G.S.)
London	16° 16′ W.	67° 9′ N.	0·47
St. Petersburg	0° 30′ E.	70° 46′ N.	0·48
Berlin	9° 30′ W.	66° 43′ N.	0·48
Paris	14° 30′ W.	64° 55′ N.	0·47
Rome	10° 0′ W.	58° 0′ N.	0·45
New York	9° 12′ W.	70° 6′ N.	0·61
Washington	4° 35′ W.	70° 18′ N.	0·60
San Francisco	16° 42′ E.	62° 20′ N.	0·54
Mexico	8° 0′ E.	45° 1′ N.	0·48
St. Helena	25° 0′ W.	32° 12′ S.	0·31
Cape Town	29° 24′ W.	58° 2′ S.	0·36
Sydney	9° 36′ E.	62° 45′ S.	0·57
Hobarton	25° 0′ E.	71° 12′ S.	0·64
Bombay	0° 36′ E.	20° 38′ N.	0·37
Tokio	4° 6′ W.	49° 52′ N.	0·45

153. **Intensity.**—Three things must be known in order to specify exactly the magnetism at any place; these three elements are:

The Declination;
The Inclination, and
The Intensity of the Magnetic Force.

The magnetic force is measured by one of the methods mentioned in the preceding lesson. Its direction is in the line of the dipping-needle, which, like every magnet, tends to set itself along the lines of force. It is, however, more convenient to measure the force not in its total intensity in the line of the dip, but to measure the horizontal component of the force,—that is to say, the force in the direction of the horizontal compass-needle, from which the total force can be calculated if the dip is known.* Or if the horizontal and vertical components of the force are known, the total force and the angle of the dip can both be calculated.† The horizontal component of the force, or "horizontal intensity," can be ascertained either by the method of Vibrations or by the method of Deflexions. The mean horizontal force of the earth's magnetism at London in 1890 was ·1823 *gausses*, the mean vertical force ·4377, the total force (in the line of dip) was ·4741 *gausses*. The distribution of the magnetic force at different points of the earth's surface is irregular, and varies in different latitudes according to an approximate law, which, as given by Biot, is that the force is proportional to $\sqrt{1 + 3\sin^2 l}$, where l is the magnetic latitude.

154. Magnetic Maps.—For purposes of convenience it is usual to construct magnetic maps, on which such data as those given in the Table on p. 139 can be marked down. Such maps may be constructed in several ways. Thus, it would be possible to take a map of England, or of the world, and mark it over with lines such as to represent by their direction the actual direction in which the compass points; in fact to draw the lines of force or

* For if H = Horizontal Component of Force, and I = Total Force, and θ = angle of dip, $I = H \div \cos\theta$.

† For $H^2 + V^2 = I^2$, where V = Vertical Component of Force.

magnetic meridians. A more useful way of marking the map is to find out those places at which the declination is the same, and to join these places by a line. The Magnetic Map of Great Britain, which forms the Frontispiece to these lessons, is constructed on this plan from the magnetic survey lately made by Rücker and Thorpe. At Plymouth the compass-needle in 1900 will point 18° to the west of the geographical north. The declination at Lynton, at Shrewsbury, and at Berwick will in that year be the same as at Plymouth. Hence a line joining these towns may be called a *line of equal declination*, or an **Isogonic line**. It will be seen from this map that the declination is greater in the north-west of England than in the south-east. We might similarly construct a magnetic map, marking it with lines joining places where the *dip* was equal; such lines would be called **Isoclinic lines**. In England they run across the map from west-south-west to east-north-east. For example, in 1900 the needle will dip about 67° at London, Southampton, and Plymouth. Through these places then the isoclinic of 67° may be drawn for that epoch. On the globe the isogonic lines run for the most part from the north magnetic pole to the south magnetic polar region, but, owing to the irregularities of distribution of the earth's magnetism, their forms are not simple. The isoclinic lines of the globe run round the earth like the parallels of latitude, but are irregular in form. Thus the line joining places where the north-seeking pole of the needle dips down 70° runs across England and Wales, passes the south of Ireland, then crosses the Atlantic in a south-westerly direction, traverses the United States, swerving northwards, and just crosses the southern tip of Alaska. It drops somewhat southward again as it crosses China, but again curves northwards as it enters Russian territory. Finally it crosses the southern part of the Baltic, and reaches England across the German Ocean. The magnetic chart of the United States, which is also given at the front of this book, is for the year

1900. It has been prepared from data furnished by Professor Mendenhall of the U.S. Geodetic Survey. It will be noticed that in the year 1900 the magnetic declination will be zero at Lansing (Mich.), Columbus (Ohio), and Charleston (S. Carolina).

The line passing through places of no declination is called the *agonic* line. It passes across both hemispheres, crossing Russia, Persia, and Australia. There is another agonic line in eastern Asia enclosing a region around Japan, within which there is a westerly declination.

155. Variations of Earth's Magnetism.—We have already mentioned that both the declination and the inclination are subject to changes; some of these changes take place very slowly, others occur every year, and others again every day.

Those changes which require many years to run their course are called *secular changes.*

The variations of the *declination* previous to 1580 are not recorded; the compass at London then pointed 11° *east* of true north. This easterly declination gradually decreased, until in 1657 the compass pointed true north. It then moved westward, attaining a maximum of 24° 27′ about the year 1816, from which time it has slowly diminished to its present value (16° 9′ in 1901); it diminishes (in England) at about the rate of 7′ per year. At about the year 1976 it will again point truly north, making a complete cycle of changes in about 320 years.

The *Inclination* in 1576 was 71° 50′, and it slowly increased till 1720, when the angle of dip reached the maximum value of 74° 42′. It has since steadily diminished to its present (1901) value of 67° 8′. The period in which the cycle is completed is not known, but the rate of variation of the dip is less at the present time than it was fifty years ago. In all parts of the earth both declination and inclination are slowly changing. The following table gives the data of the secular changes at London.

TABLE OF SECULAR MAGNETIC VARIATIONS

Year.	Declination.	Inclination.
1576		71° 50′
1580	11° 17′ E.	
1600		72° 0′
1622	6° 12′	
1634	4° 0′	
1657	0° 0′ min.	
1676	3° 0′ W.	73° 30′
1705	9° 0′	
1720	13° 0′	74° 42′ max.
1760	19° 30′	
1780		72° 8′
1800	24° 6′	70° 35′
1816	24° 30′ max.	
1830	24° 2′	69° 3′
1855	23° 0′	
1868	20° 33′	68° 2′
1878	19° 14′	67° 43′
1880	18° 40′	67° 40′
1890	17° 26′	67° 23′
1900	16° 16′	67° 9′
1910	15° 3′	66° 54′

The *Total Magnetic force*, or "Intensity," also slowly changes in value. As measured near London, it was equal to ·4791 *gausses* in 1848, ·4740 in 1866, in 1880 ·4736 *gausses*, in 1890 ·4741.* Owing to the steady decrease of the angle at which the needle dips, the horizontal component of this force (*i.e.* the "Horizontal Intensity") is slightly increasing. It was ·1716 *gausses* in 1814, ·1797 *gausses* at the beginning of 1880, and ·1823 *gausses* in 1890.

156. Daily Variations.—Both compass and dipping-needle, if minutely observed, exhibit slight daily

* That is to say, a north magnet pole of unit strength is urged in the line of dip, with a mechanical force of a little less than half a dyne.

motions. About 7 A.M. the compass-needle begins to travel westward with a motion which lasts till about 1 P.M.; during the afternoon and evening the needle slowly travels back eastward, until about 10 P.M.; after this it rests quiet; but in summer-time the needle begins to move again slightly to the west at about midnight, and returns again eastward before 7 A.M. These delicate variations—never more than 10′ of arc—appear to be connected with the position of the sun; and the moon also exercises a minute influence upon the position of the needle.

157. Annual Variations.—There is also an annual variation corresponding with the movement of the earth around the sun. In the British Islands the total force is greatest in June and least in February, but in the Southern Hemisphere, in Tasmania, the reverse is the case. The dip also differs with the season of the year, the angle of dip being (in England) less during the four summer months than in the rest of the year.

158. Eleven-Year Period.—General Sabine discovered that there is a larger amount of variation of the declination occurring about once every eleven years. Schwabe noticed that the recurrence of these periods coincided with the eleven-year periods at which there is a maximum of *spots* on the sun. Professor Balfour Stewart and others have endeavoured to trace a similar periodicity in the recurrence of **auroræ** * and of other phenomena.

159. Magnetic Storms.—It is sometimes observed that a sudden (though very minute) irregular disturbance will affect the whole of the compass-needles over a considerable region of the globe. Such occurrences are known as magnetic storms; they frequently occur at the time when an aurora is visible.

160. Self-recording Magnetic Apparatus.—At Kew and other magnetic observatories the daily and

* See Lesson XXIV., on Atmospheric Electricity.

hourly variations of the magnet are recorded on a continuous register. The means employed consists in throwing a beam of light from a lamp on to a light mirror attached to the magnet whose motion is to be observed. A spot of light is thus reflected upon a ribbon of photographic paper prepared so as to be sensitive to light. The paper is moved continuously forward by a clock-work train; and if the magnet be at rest the dark trace on the paper will be simply a straight line. If, however, the magnet moves aside, the spot of light reflected from the mirror will be displaced, and the photographed line will be curved or crooked. Comparison of such records, or *magnetographs*, from stations widely apart on the earth's surface, promises to afford much light upon the *cause* of the changes of the earth's magnetism, to which hitherto no reliable origin has been with certainty assigned. Schuster has shown that these changes generally come from without, and not from within.

161. Theory of Earth's Magnetism.—The phenomenon of earth-currents (Art. 233) appears to be connected with that of the changes in the earth's magnetism, and can be observed whenever there is a display of aurora, and during a magnetic storm; but it is not yet determined whether these currents are due to the variations in the magnetism of the earth, or whether these variations are due to the currents. It is known that the evaporation (see Art. 71) always going on in the tropics causes the ascending currents of heated air to be electrified positively relatively to the earth. These air-currents travel northward and southward toward the colder polar regions, where they descend. These streams of electrified air will act (see Art. 397) like true electric currents, and as the earth rotates within them it will be acted upon magnetically. The author has for twelve years upheld the view that this thermodynamic production of polar currents in conjunction with the earth's diurnal rotation affords the only rational means yet

suggested for accounting for the growth of the earth's magnetism to its present state. The action of the sun and moon in raising tides in the atmosphere might account for the variations mentioned in Art. 155. It is important to note that in all magnetic storms the intensity of the perturbations is greatest in the regions nearest the poles; also, that the magnetic poles coincide very nearly with the regions of greatest cold; that the region where auroræ (Art. 336) are seen in greatest abundance is a region lying nearly symmetrically round the magnetic pole. It may be added that the general direction of the feeble daily earth-currents (Art. 233) is from the poles toward the equator.

CHAPTER III

CURRENT ELECTRICITY

Lesson XIII.—*Simple Voltaic Cells*

162. Flow of Currents.—It has been already mentioned, in Lesson IV., how electricity flows away from a charged body through any conducting substance, such as a wire or a wetted string. If, by any arrangement, electricity could be supplied to the body just as fast as it flowed away, a continuous **current** would be produced. Such a current always flows through a conducting wire, if the ends are kept at different electric potentials. In like manner, a current of heat flows through a rod of metal if the ends are kept at different temperatures, the flow being always from the high temperature to the lower. No exact evidence exists as to the direction in which the current in a wire really "flows." It is convenient to regard the electricity as flowing from positive to negative; or, in other words, the natural direction of an electric current is from the high potential to the low. It is obvious that such a flow tends to bring both to one level of potential. In order that a continuous flow may be kept up there must be a *circuit* provided. The "current" has sometimes been regarded as a double transfer of positive electricity in one direction, and of negative electricity in the opposite direction. The only evidence to support this very un-

necessary supposition is the fact that, in the decomposition of liquids by the current, some of the elements are liberated at the place where the current enters, others at the place where it leaves the liquid.

The quantity of electricity conveyed by a current is proportional to the current and to the time that it continues to flow. The practical unit of current is called the *ampere* (see Arts. 207 and 254). The quantity of electricity conveyed by a current of one *ampere* in one second is called one *ampere-second* or one *coulomb*. One *ampere-hour* equals 3600 *coulombs*. If C is the number of amperes of current, t the number of seconds that it lasts, and Q the number of coulombs of electricity thereby conveyed, the relation between them is expressed by the formula :—

$$Q = C \times t.$$

Example.—If a current of 80 amperes flows for 15 minutes the total quantity of electricity conveyed will be $80 \times 15 \times 60 = 72{,}000$ coulombs. This is equal to 20 ampere-hours.

Currents are called *continuous* if they flow, without stopping, in one direction. They are called *alternate currents* if they continually reverse in direction in a regular periodic manner, flowing first in one direction round the circuit and then in the other.

Continuous currents of electricity, such as we have described, are produced by *voltaic cells*, and *batteries* of such cells, or else by *dynamos* driven by power, though there are other sources of currents hereafter to be mentioned. Alternate currents are produced by special alternate current dynamos or *alternators*, and are separately treated of in Art. 470.

163. Discoveries of Galvani and of Volta.—The discovery of electric currents originated with *Galvani*, a physician of Bologna, who, about the year 1786, made a series of curious and important observations upon the

convulsive motions produced by the "return-shock" (Art. 29) and other electric discharges upon a frog's leg. He was led by this to the discovery that it was not necessary to use an electric machine to produce these effects, but that a similar convulsive kick was produced in the frog's leg when two dissimilar metals, iron and copper, for example, were placed in contact with a nerve and a muscle respectively, and then brought into contact with each other. Galvani imagined this action to be due to electricity generated by the frog's leg itself. It was, however, proved by *Volta*, Professor in the University of Pavia, that the electricity arose not from the muscle or nerve, but from the contact of the dissimilar metals. When two metals are placed in contact with one another in the air, one becomes positive and the other negative, as we have seen near the end of Lesson VII., though the charges are very feeble. Volta, however, proved their reality by two different methods.

164. The Voltaic Pile.—The second of Volta's proofs was less direct, but even more convincing; and consisted in showing that when a number of such contacts of dissimilar metals could be arranged so as to add their electrical effects together, those effects were more powerful in proportion to the number of the contacts. With this view he constructed the apparatus known (in honour of the discoverer) as the **Voltaic Pile** (Fig. 95). It is made by placing a pair of disks of zinc and copper in contact with one another, then laying on the copper disk a piece of flannel or blotting-paper moistened with brine, then another pair of disks of zinc and copper, and so on, each pair of disks in the pile being separated by a moist conductor. Such a *pile*, if composed of a number of such pairs of disks, will produce electricity

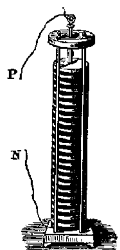


Fig. 95.

enough to give quite a perceptible shock, if the top and bottom disks, or wires connected with them, be touched simultaneously with the moist fingers. When a single pair of metals are placed in contact, one becomes +ly electrical to a certain small extent, and the other −ly electrical, or, in other words, there is a certain difference of electric potential (see Art. 265) between them. But when a number are thus set in series with moist conductors between the successive pairs, the difference of potential between the first zinc and the last copper disk is increased in proportion to the number of pairs; for now all the successive small differences of potential are added together.

165. The Crown of Cups.—Another combination devised by Volta was his *Couronne de Tasses* or *Crown of Cups.* It consisted of a number of cups (Fig. 96), filled either with brine or dilute acid, into which dipped a number of compound strips, half zinc half copper, the zinc portion of one strip dipping into one cup, while

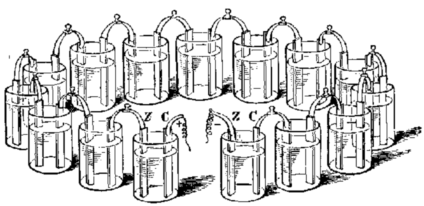


Fig. 96.

the copper portion dipped into the other cup. The difference of potential between the first and last cups is again proportional to the number of pairs of metal strips. This arrangement, though badly adapted for such a purpose, is powerful enough to ring an electric bell, the wires of which are joined to the first zinc and the last copper strip. The electrical action of these

combinations is, however, best understood by studying the phenomena of one single cup or *cell.*

166. Simple Voltaic Cell.—Place in a glass jar some water having a little sulphuric acid or any other oxidizing acid added to it (Fig. 97). Place in it separately two clean strips, one of zinc Z, and one of copper C. This cell is capable of supplying a continuous flow of electricity through a wire whose ends are brought into connexion with the two strips. When the current flows the zinc strip is observed to waste away; its consumption in fact furnishes the energy required to drive the current through the cell and the connecting wire. The cell may therefore be regarded as a sort of chemical furnace in which fuel is consumed to drive the current. The zinc is the fuel,* the acid is the aliment, whilst the copper is merely a metallic hand let down into the cell to pick up the current, and takes no part chemically. Before the strips are connected by a wire no appreciable difference of potential between the copper and the zinc will be observed by an electrometer; because the electrometer only measures the potential at a point in the air or oxidizing medium outside the zinc or the copper, not the

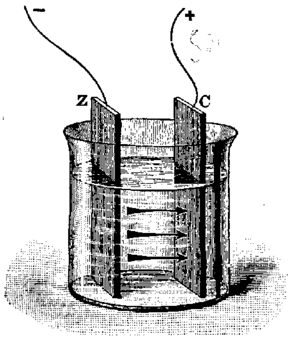


Fig. 97.

* Zinc, as is well known, will burn with a blue flame in air or oxygen, giving out heat. Zinc foil is easily kindled.

potentials of the metals themselves. The zinc is trying to dissolve and throw a current across to the copper; while the copper is trying (less powerfully) to dissolve and throw a current across the other way. The zinc itself is at about 1·86 volts higher potential than the surrounding oxidizing media (see Art. 489); while the copper is at only about ·81 volts higher, having a less tendency to become oxidized. There is then a latent difference of potential of about 1·05 volts between the zinc and the copper; but this produces no current as long as there is no metallic circuit. If the strips are made to touch, or are joined by a pair of metal wires, immediately there is a rush of electricity through the acid from the zinc to the copper, as indicated by the arrows in Fig. 97, the current returning by the metal circuit from the copper to the zinc. A small portion of the zinc is at the same time dissolved away; the zinc parting with its latent energy as its atoms combine with the acid. This energy is expended in forcing electricity through the acid to the copper strip, and thence through the wire circuit back to the zinc strip. The copper strip, whence the current starts on its journey through the external circuit, is called the *positive pole*, and the zinc strip is called the *negative pole*. If two copper wires are united to the tops of the two strips, though no current flows so long as the wires are kept separate, the wire attached to the zinc will be found to be negative, and that attached to the copper positive, there being still a *tendency* for the zinc to oxidize and drive electricity through the cell from zinc to copper. This state of things is represented by the + and − signs in Fig. 97; and this distribution of potentials led some to consider the junction of the zinc with the copper wire as the starting point of the current. But the real starting point is in the cell at the surface of the zinc where the chemical action is furnishing energy; for from this point there are propagated through the liquid certain electro-chemical actions (more fully ex-

plained in Chap. XI.) which have the result of constantly renewing the difference of potential. At the same time it will be noticed that a few bubbles of hydrogen gas appear on the surface of the copper plate. Both these actions go on as long as the wires are joined to form a complete circuit. The metallic zinc may be considered as a store of energy. We know that if burned as a fuel in oxygen or air it will give out that store of energy as heat. If burned in this quiet chemical manner in a cell it gives out its store not as heat—any heat in a cell is so much waste—but in the form of electric energy, *i.e.* the energy of an electric current propelled by an electromotive force.

167. Effects produced by Current.—The current itself cannot be *seen* to flow through the wire circuit; hence to prove that any particular cell or combination produces a current requires a knowledge of some of the *effects* which currents can produce. These are of various kinds. A current flowing through a thin wire will heat it; flowing near a magnetic needle it will cause it to turn aside; flowing through water and other liquids it decomposes them; and, lastly, flowing through the living body or any sensitive portion of it, it produces certain sensations. These effects, thermal, magnetic, chemical, and physiological, will be considered in special lessons.

168. Voltaic Battery.—If a number of such simple cells are united in series, the zinc plate of one joined to the copper plate of the next, and so on, a greater difference of potentials will be produced between the copper "pole" at one end of the series and the zinc "pole" at the other end. Hence, when the two poles are joined by a wire there will be a more powerful flow of electricity than one cell would cause. Such a combination of Voltaic Cells is called a Voltaic **Battery.*** There are

* By some writers the name *Galvanic* Battery is given in honour of Galvani; but the honour is certainly Volta's. The electricity that flows thus in currents is sometimes called *Voltaic Electricity*, or *Galvanic*

many ways of grouping a battery of cells, but two need special notice. If the cells are joined up in one row, as in Fig. 96 or Fig. 98, they are said to be *in series*. Electricians often represent a cell by a symbol in which a short thick line stands for the zinc and a longer thin line for the copper (or carbon). Thus Fig. 98 represents four cells joined in series. The maximum current (*amperes*) which so grouped they will yield is not more than a single cell would yield on short circuit; but they yield that current with a fourfold electromotive-force (*volts.*)

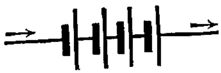


Fig. 98.

The other chief way of grouping cells is to join all the zincs together and all the coppers (or carbons) together; and they are then said to be *in parallel*, or are joined "for quantity." So joined they have no greater electromotive-force than one cell. The zincs act like one big zinc, the coppers like one big copper. But they will yield more current. Fig. 99 shows the four cells grouped *in parallel;* they would yield thus a current four times as great as one cell alone would yield.

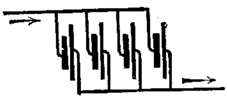


Fig. 99.

169. Electromotive-Force.—The term *electromotive-force* is employed to denote that which moves or tends to move electricity from one place to another.*

Electricity, or sometimes even *Galvanism* (!), but, as we shall see, it differs only in degree from Frictional or any other Electricity, and both can flow along wires, and magnetize iron, and decompose chemical compounds. The word *Battery* means an arrangement of one or more cells; just as in warfare a battery of guns means an arrangement of one or more.

* The beginner must not confuse *Electromotive-force*, or that which tends to move electricity, with *Electric* "*force*," or that force with which electricity tends to move matter. Newton has virtually defined "force," once for all, as that which moves or tends to move matter. When matter is moved by a magnet we speak rightly of *magnetic force;* when electricity

For brevity we sometimes write it E.M.F. In this particular case it is obviously the result of the difference of potential, and proportional to it. Just as in water-pipes a *difference of level* produces a *pressure*, and the pressure produces a *flow* so soon as the tap is turned on, so *difference of potential* produces *electromotive-force*, and electromotive-force sets up a *current* so soon as a circuit is completed for the electricity to flow through. Electromotive-force, therefore, may often be conveniently expressed as a difference of potential, and *vice versâ*; but the student must not forget the distinction. The unit in which electromotive-force is measured is termed the *volt* (see Art. 354). The terms *pressure* and *voltage* are sometimes used for difference of potential or electromotive-force.

170. Volta's Laws.—Volta showed (Art. 79) that the difference of potential between two metals in contact (in air) depended merely on what metals they were, not on their size, nor on the amount of surface in contact. He also showed that when a number of metals touched one another the difference of potential between the first and last of the row is the same as if they touched one another directly. A quantitative illustration from the researches of Ayrton and Perry was given in Art. 80. But the case of a series of cells is different from that of a mere row of metals in contact. If in the row of cells the zincs and coppers are all arranged in one order, so that all of them set up electromotive-forces in the same direction, *the total electromotive-force of the series will be equal to the electromotive-force of one cell multiplied by the number of cells.*

Hitherto we have spoken only of zinc and copper as the materials for a cell; but cells may be made of any two metals. The effective electromotive-force of a cell depends on the *difference* between the two. If zinc was

moves matter we may speak of *electric force*. But E.M.F. is quite a different thing, not "force" at all, for it acts not on matter but on electricity, and tends to move it.

used for both metals in a cell it would give no current, for each plate would be trying to dissolve and to throw a current across to the other with equal tendency. That cell will have the greatest electromotive-force, or be the most "intense," in which those materials are used which have the greatest difference in their tendency to combine chemically with the acid, or which are widest apart on the "contact-series" given in Art. 80. Zinc and copper are convenient in this respect; and zinc and silver would be better but for the expense. For more powerful batteries a zinc-platinum or a zinc-carbon combination is preferable. That plate or piece of metal in a cell by which the current enters the liquid is called the *anode;* it is that plate which dissolves away. The plate or piece of metal by which the current leaves the cell is called the *kathode;* it is not dissolved, and in some cases receives a deposit on its surface.

171. Resistance.—The same electromotive-force does not, however, always produce a current of the same *strength.* The amount of current depends not only on the force tending to drive the electricity round the circuit, but also on the **resistance** which it has to encounter and overcome in its flow. If the cells be partly choked with sand or sawdust (as is sometimes done in so-called "Sawdust Batteries" to prevent spilling), or, if the wire provided to complete the circuit be very long or very thin, the action will be partly stopped, and the current will be weaker, although the E.M.F. may be unchanged. The analogy of the water-pipes will again help us. The pressure which forces the water through pipes depends upon the difference of level between the cistern from which the water flows and the tap to which it flows; but the amount of water that runs through will depend not on the pressure alone, but on the resistance it meets with; for, if the pipe be a very thin one, or choked with sand or sawdust, the water will only run slowly through.

Now the metals in general conduct well: their resistance is small; but metal wires must not be too thin or too long, or they will resist too much, and permit only a feeble current to pass through them. The liquids in the cell do not conduct nearly so well as the metals, and different liquids have different resistances. Pure water will hardly conduct at all, and is for the feeble electricity of the voltaic battery almost a perfect insulator, though for the high-potential electricity of the frictional machines it is, as we have seen, a fair conductor. Salt and saltpetre dissolved in water are good conductors, and so are dilute acids, though strong sulphuric acid is a bad conductor. The resistance of the liquid in the cells may be reduced, if desired, by using larger plates of metal and putting them nearer together. Gases are bad conductors; hence the bubbles of hydrogen gas which are given off at the copper plate during the action of the cell, and which stick to the surface of the copper plate, increase the internal resistance of the cell by diminishing the effective surface of the plates.

LESSON XIV.—*Chemical Actions in the Cell*

172. Chemical Actions.—The production of a current of electricity by a voltaic cell is *always* accompanied by chemical actions in the cell. One of the metals at least must be readily oxidizable, and the liquid must be one capable of acting on the metal. As a matter of fact, it is found that zinc and the other metals which stand at the electropositive end of the contact-series (see Art. 80) are oxidizable; whilst the electronegative substances—copper, silver, gold, platinum, and graphite—are less oxidizable, and the last three resist the action of every single acid. There is no proof that their electrical behaviour is due to their chemical behaviour; nor that their chemical behaviour is due to their electrical.

Probably both result from a common cause (see Art. 80, and also 489). A piece of quite pure zinc when dipped alone into dilute sulphuric acid is not attacked by the liquid. But the ordinary commercial zinc is not pure, and when plunged into dilute sulphuric acid dissolves away, a large quantity of bubbles of hydrogen gas being given off from the surface of the metal. Sulphuric acid is a complex substance, in which every molecule is made up of a group of atoms—2 of Hydrogen, 1 of Sulphur, and 4 of Oxygen; or, in symbols, H_2SO_4. The chemical reaction by which the zinc enters into combination with the radical of the acid, turning out the hydrogen, is expressed in the following equation:—

$$\underset{\text{Zinc}}{Zn} \underset{\text{and}}{+} \underset{\text{Sulphuric Acid}}{H_2SO_4} \underset{\text{produce}}{=} \underset{\text{Sulphate of Zinc}}{ZnSO_4} \underset{\text{and}}{+} \underset{\text{Hydrogen.}}{H_2}$$

The sulphate of zinc produced in this reaction remains in solution in the liquid.

Now, when a plate of pure zinc and a plate of some less-easily oxidizable metal—copper or platinum, or, best of all, carbon (the hard carbon from gas retorts)—are put side by side into the cell containing acid, no appreciable chemical action takes place until the circuit is completed by joining the two plates with a wire, or by making them touch one another. Directly the circuit is completed a current flows and the chemical actions begin, the zinc dissolving in the acid, and the acid giving up its hydrogen in streams of bubbles. But it will be noticed that these bubbles of hydrogen are evolved *not* at the zinc plate, nor yet throughout the liquid, but *at the surface of the copper plate* (or the carbon plate if carbon is employed). This apparent transfer of the hydrogen gas through the liquid from the surface of the zinc plate to the surface of the copper plate where it appears is very remarkable. The ingenious theory framed by Grotthuss to account for it is explained in Lesson XLVII. on Electro-Chemistry.

These chemical actions go on as long as the current passes. The quantity of zinc used up *in each cell* is proportional to the amount of electricity which flows round the circuit while the battery is at work; or, in other words, is proportional to the current. The quantity of hydrogen gas evolved is also proportional to the amount of zinc consumed, and also to the current. After the acid has thus dissolved zinc in it, it will no longer act as a corrosive solvent; it has been "killed," as workmen say, for it has been turned into sulphate of zinc. The battery will cease to act, therefore, either when the zinc has all dissolved away, or when the acid has become exhausted, that is to say, when it is all turned into sulphate of zinc. Stout zinc plates will last a long time, but the acids require to be renewed frequently, the spent liquor being emptied out.

173. **Local Action.**—When the circuit is not closed the current cannot flow, and there should be no chemical action so long as the battery is producing no current. The impure zinc of commerce, however, does not remain quiescent in the acid, but is continually dissolving and giving off hydrogen bubbles. This **local action**, as it is termed, is explained in the following manner:—The impurities in the zinc consist of particles of iron, arsenic, and other metals. Suppose a particle of iron to be on the surface anywhere and in contact with the acid. It will behave like the copper plate of a battery towards the zinc particles in its neighbourhood, for a local difference of potential will be set up at the point where there is metallic contact, causing a local or parasitic current to run from the particles of zinc through the acid to the particle of iron, and so there will be a continual wasting of the zinc, both when the battery circuit is closed and when it is open.

174. **Amalgamation of Zinc.**—We see now why a piece of ordinary commercial zinc is attacked on being placed in acid. There is local action set up all over its

surface in consequence of the metallic impurities in it. To do away with this local action, and abolish the wasting of the zinc while the battery is at rest, it is usual to **amalgamate** the surface of the zinc plates with mercury. The surface to be amalgamated should be cleaned by dipping into acid, and then a few drops of mercury should be poured over the surface and rubbed into it with a bit of linen rag tied to a stick. The mercury unites with the zinc at the surface, forming a pasty amalgam. The iron particles do not dissolve in the mercury, but float up to the surface, whence the hydrogen bubbles which may form speedily carry them off. As the zinc in this pasty amalgam dissolves into the acid the film of mercury unites with fresh portions of zinc, and so presents always a clean bright surface to the liquid.

A newer and better process is to add about 4 per cent of mercury to the molten zinc before casting into plates or rods. If the zinc plates of a battery are well amalgamated there should be no evolution of hydrogen bubbles when the circuit is open. Nevertheless there is still always a little wasteful local action during the action of the battery. Jacobi found that while one part of hydrogen was evolved at the kathode, 33·6 parts of zinc were dissolved at the anode, instead of the 32·5 parts which are the chemical equivalent of the hydrogen.

175. Polarization.—The bubbles of hydrogen gas liberated at the surface of the copper plate stick to it in great numbers, and form a film over its surface; hence the effective amount of surface of the copper plate is very seriously reduced in a short time. When a simple cell, or battery of such cells, is set to produce a current, it is found that the current after a few minutes, or even seconds, falls off very greatly, and may even be almost stopped. This immediate falling off in the current, which can be observed with any galvanometer and a pair of zinc and copper plates dipping into acid, is almost entirely due

to the film of hydrogen bubbles sticking to the copper pole. A battery which is in this condition is said to be "**polarized.**"

176. Effects of Polarization.—The film of hydrogen bubbles affects the strength of the current of the cell in two ways.

Firstly, it weakens the current by the increased *resistance* which it offers to the flow, for bubbles of gas are bad conductors; and, worse than this,

Secondly, it weakens the current by setting up an opposing *electromotive-force;* for hydrogen is almost as oxidizable a substance as zinc, especially when it is being deposited (or in a "nascent" state), and is electropositive, standing high in the series on p. 85. Hence the hydrogen itself produces a difference of potential, which would tend to start a current in the opposite direction to the true zinc-to-copper current. No cell in which the polarization causes a rapid falling off in power can be used for closed circuit work.

It is therefore a very important matter to abolish this polarization, otherwise the currents furnished by batteries would not be constant.

177. Remedies against Internal Polarization.—Various remedies have been practised to reduce or prevent the polarization of cells. These may be classed as mechanical, chemical, and electrochemical.

1. *Mechanical Means.*—If the hydrogen bubbles be simply brushed away from the surface of the kathode, the resistance they caused will be diminished. If air be blown into the acid solution through a tube, or if the liquid be agitated or kept in constant circulation by siphons, the resistance is also diminished. If the surface be rough or covered with points, the bubbles collect more freely at the points and are quickly carried up to the surface, and so got rid of. This remedy was applied in **Smee's Cell**, which consisted of a zinc and a platinized silver plate dipping into dilute sulphuric acid; the silver

plate, having its surface thus covered with a rough coating of finely divided platinum, gave up the hydrogen bubbles freely; nevertheless, in a battery of Smee cells the current diminishes greatly after a few minutes.

2. *Chemical Means.*—If a highly-oxidizing substance be added to the acid it will destroy the hydrogen bubbles whilst they are still in the nascent state, and thus will prevent both the increased internal resistance and the opposing electromotive-force. Such substances are bichromate of potash, nitric acid, and chlorine.

3. *Electrochemical Means.*—It is possible by employing double cells, as explained in the next lesson, to so arrange matters that some solid metal, such as *copper*, shall be liberated instead of hydrogen bubbles, at the point where the current leaves the liquid. This electrochemical exchange entirely obviates polarization.

178. Simple Laws of Chemical Action in the Cell.—We will conclude this section by enumerating the two simple laws of chemical action in the cell.

I. *The amount of chemical action in the cell is proportional to the quantity of electricity that passes through it*—that is to say, is proportional to *the current* while it passes.

A current of one *ampere* flowing through the cell for one second causes 0·00033698 (or $\frac{1}{2967}$) of a gramme of zinc to dissolve in the acid, and liberates 0·000010384 (or $\frac{1}{96302}$) of a gramme of hydrogen.

II. *The amount of chemical action is equal in each cell* of a battery consisting of cells joined in series.

The first of these laws was thought by Faraday, who discovered it, to disprove Volta's contact theory. He foresaw that the principle of the conservation of energy would preclude a mere contact force from furnishing a continuous supply of current, and hence ascribed the current to the chemical actions which were proportional in quantity to it. How the views of Volta and Faraday are to be harmonized has been indicated in the last

paragraph of Art. 80. These laws only relate to the useful chemical action, and do not include the waste of "local" actions (Art. 166) due to parasitic currents set up by impurities.

LESSON XV.—*Voltaic Cells*

179. A good Voltaic cell should fulfil all or most of the following conditions :—

1. Its electromotive-force should be high and constant.
2. Its internal resistance should be small.
3. It should give a constant current, and therefore must be free from polarization, and not liable to rapid exhaustion, requiring frequent renewal of the acid.
4. It should be perfectly quiescent when the circuit is open.
5. It should be cheap and of durable materials.
6. It should be manageable, and if possible, should not emit corrosive fumes.

No single cell fulfils all these conditions, however, and some cells are better for one purpose and some for another. Thus, for telegraphing through a long line of wire a considerable internal resistance in the battery is no great disadvantage ; while, for producing an electric light, much internal resistance is absolutely fatal. The electromotive-force of a battery depends on the materials of the cell, and on the number of cells linked together, and a high E.M.F. can therefore be gained by choosing the right substances and by taking a large number of cells. The resistance within the cell can be diminished by increasing the size of the plates, by bringing them near together, so that the thickness of the liquid between them may be as small as possible, and by choosing liquids that are good conductors.

180. Classification of Cells.—Of the innumerable forms of cell that have been invented, only those of first importance can be described. Cells are sometimes classified into two groups, according as they contain one or two fluids, or electrolytes, but a better classification is that adopted in Art. 177, depending on the means of preventing polarization.

Class I.—With Mechanical Depolarization
(Single Fluid)

The simple cell of Volta, with its zinc and copper plates, has been already described. The larger the copper plate, the longer time does it take to polarize. Cruickshank suggested to place the plates vertically in a trough, producing a more powerful combination. Dr. Wollaston proposed to use a plate of copper of double size, bent round so as to approach the zinc on both sides, thus diminishing the resistance, and allowing the hydrogen more surface to deposit upon. Smee, as we have seen, replaced the copper plate by platinized silver, and Walker suggested the use of plates of hard carbon instead of copper or silver, thereby saving cost, and at the same time increasing the electromotive-force. The roughness of the surface facilitates the escape of hydrogen bubbles. By agitating such cells, or raising their kathode plates for a few moments into the air, their power is partially restored. The Law cell, used in the United States for open-circuit work, is of this class: it has a small rod of zinc and a cleft cylinder of carbon of large surface immersed in solution of salammoniac.

Class II.—With Chemical Depolarization

In these cells, in addition to the dilute acid or other *excitant* to dissolve the zinc, there is added some more

powerful chemical agent as a *depolarizer*. Amongst depolarizers the following are chiefly used :—Nitric acid, solutions of chromic acid, of bichromate of potash, of bichromate of soda, of nitrate of potash, or of ferric chloride; chlorine, bromine, black oxide of manganese, sulphur, peroxide of lead, red lead, oxide of copper. Most of these materials would, however, attack the copper as well as the zinc if used in a zinc-copper cell. Hence they can only be made use of in zinc-carbon or zinc-platinum cells. Nitric acid also attacks zinc when the circuit is open. Hence it cannot be employed in the same single cell with the zinc plate. In the **Bichromate Cell**, invented by Poggendorff, bichromate of potash is added to the sulphuric acid. This cell is most conveniently made up as shown in Fig. 100, in which a plate of zinc is the anode, and a pair of carbon plates, one on each side of the zinc, joined together at the top serve as a kathode. As this solution would attack the zinc even when the circuit is open, the zinc plate is fixed to a rod by which it can be drawn up out of the solution when the cell is not being worked.

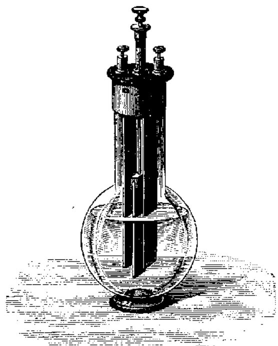


Fig. 100.

To obviate the necessity of this operation the device is adopted of separating the depolarizer from the liquid into which the zinc dips. In the case of liquid depolarizers this is done by the use of an internal *porous cell* or partition. Porous cells of earthenware or of parchment paper

allow the electric current to flow while keeping the liquids apart. In one compartment is the zinc anode dipping into its aliment of dilute acid : in the other compartment the carbon (or platinum) kathode dipping into the depolarizer. Such cells are termed *two-fluid cells.* In the case of solid depolarizers such as black oxide of manganese, oxide of copper, etc., the material merely needs to be held up to the kathode. All solid depolarizers are *slow* in acting.

CLASS III.—WITH ELECTROCHEMICAL DEPOLARIZATION

When any soluble metal is immersed in a solution of its own salt—for example, zinc dipped into sulphate of zinc, or copper into sulphate of copper—there is a definite electromotive-force between it and its solution, the measure of its tendency to dissolve. If a current is sent from metal to solution some of the metal dissolves; if, however, the current is sent from solution to metal some more metal will be deposited (or "plated") out of the solution. But as long as the chemical nature of the surface and of the liquid is unchanged there will be no change in the electromotive-force at the surface. It follows that if a cell were made with two metals, each dipping into a solution of its own salt, the two solutions being kept apart by a porous partition, such a cell would never change its electromotive-force. The anode would not polarize where it dissolves into the excitant; the kathode would not polarize, since it receives merely an additional thickness of the same sort as itself. This electrochemical method of avoiding polarization was discovered by Daniell. It is the principle not only of the Daniell cell, but of the Clark cell and of others. For perfect constancy the two salts used should be salts of the same acid, both sulphates, or both chlorides, for example.

181. Daniell's Cell.—Each cell or "element" of

Daniell's battery has an inner porous cell or partition to keep the separate liquids from mixing. The outer cell (Fig. 101) is usually of copper, and serves also as a copper kathode. Within it is placed a cylindrical cell of unglazed porous ware (a cell of parchment, or even of brown paper, will answer), and in this is a rod of amalgamated zinc as anode. The liquid in the inner cell is dilute sulphuric acid or dilute sulphate of zinc; that in the outer cell is a saturated solution of sulphate of copper ("blue vitriol"), some spare crystals of the same substance being contained in a perforated shelf at the top of the cell, in order that they may dissolve and replace that which is used up while the battery is in action.

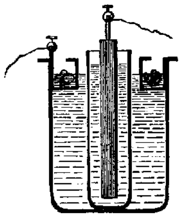


Fig. 101.

When the circuit is closed the zinc dissolves in the dilute acid, forming sulphate of zinc, and liberating hydrogen; but this gas does *not* appear in bubbles on the surface of the copper cell, for, since the inner cell is porous, the molecular actions (by which the freed atoms of hydrogen are, as explained by Fig. 266, handed on through the acid) traverse the pores of the inner cell, and there, in the solution of sulphate of copper, the hydrogen atoms are exchanged for copper atoms, the result being that pure copper, and not hydrogen gas, is deposited on the outer copper plate. Chemically these actions may be represented as taking place in two stages.

$$\underset{\text{Zinc}}{Zn} \quad \underset{\text{and Sulphuric Acid}}{+ \quad H_2SO_4} \quad \underset{\text{produce}}{=} \quad \underset{\text{Sulphate of Zinc}}{ZnSO_4} \quad \underset{\text{and Hydrogen.}}{+ \quad H_2}$$

And then

$$\underset{\text{Hydrogen}}{H_2} \quad \underset{\text{and Sulphate of Copper}}{+ \quad CuSO_4} \quad \underset{\text{produce}}{=} \quad \underset{\text{Sulphuric Acid}}{H_2SO_4} \quad \underset{\text{and Copper.}}{+ \quad Cu.}$$

The hydrogen is, as it were, translated electro-chemically into copper during the round of changes, and so while the zinc dissolves away the copper grows, the dilute sulphuric acid gradually changing into sulphate of zinc, and the sulphate of copper into sulphuric acid. In the case in which a solution of sulphate of zinc is used there is no need to consider any hydrogen atoms, copper being exchanged chemically for zinc. There is therefore no polarization so long as the copper solution is saturated; and the cell is very constant, though not so constant in all cases as Clark's standard cell described in Art. 188, owing to slight variations in the electromotive-force as the composition of the other fluid varies. When sulphuric acid diluted with twelve parts of water is used the E.M.F. is 1·178 volts. The E.M.F. is 1·07 volts when concentrated zinc sulphate is used; 1·1 volts when a half-concentrated solution of zinc sulphate is used; and, in the common cells made up with water or dilute acid, 1·1 volts or less. Owing to its constancy, this battery, made up in a convenient flat form (Fig. 106), has been much used in telegraphy. It is indispensable in those "closed circuit" methods of telegraphy (Art. 500), where the current is kept always flowing until interrupted by signalling.

182. Grove's Cell.—Sir William Grove devised a form of cell having both higher voltage and smaller internal resistance than Daniell's cell. In Grove's element there is an outer cell of glazed ware or of ebonite, containing the amalgamated zinc plate and dilute sulphuric acid. In the inner porous cell a piece of platinum foil serves as the negative pole, and it dips into the strongest nitric acid. There is no polarization in this cell, for the hydrogen liberated by the solution of the zinc in dilute sulphuric acid, in passing through the nitric acid in order to appear at the platinum pole, decomposes the nitric acid and is itself oxidized, producing water and the red fumes of nitric peroxide gas. This

gas does not, however, produce polarization, for as it is very soluble in nitric acid, it does not form a film upon the face of the platinum plate, nor does it, like hydrogen, set up an opposing electromotive-force with the zinc. The Grove cells may be made of a flat shape, the zinc being bent up so as to embrace the flat porous cell on both sides. This reduces the internal resistance, which is already small on account of the good conducting powers of nitric acid. Hence the Grove's cell will furnish for three or four hours continuously a strong current. The E.M.F. of one cell is about 1·9 volts, and its internal resistance is very low (about 0·1 *ohm* for the quart size). A single cell will readily raise to a bright red heat two or three inches of thin platinum wire, or drive a small electromagnetic engine. For producing larger power a number of cells must be joined up in series, the platinum of one cell being clamped to the zinc of the next to it. Fifty such cells, each holding about a quart of liquid, amply suffice to produce an electric arc light, as will be explained in Lesson XXXIX.

183. Bunsen's Cell.—The cell which bears Bunsen's name is a modification of that of Grove, and was indeed originally suggested by him. In the Bunsen cell the expensive * platinum foil is replaced by a rod or slab of hard gas carbon. A cylindrical form of cell, with a rod of carbon, is shown in Fig. 102. The voltage for a zinc-carbon combination is a little higher than for a zinc-platinum one, which is an advantage; but the Bunsen cell is troublesome to keep in order, and there is some difficulty in making a good contact between the rough surface of the carbon and the copper strap which connects

* Platinum costs about 30 shillings an ounce—nearly half as much as gold; while a hundredweight of the gas carbon may be had for a mere trifle, often for nothing more than the cost of carrying it from the gasworks. An artificial carbon prepared by grinding up gas carbon with some carbonaceous matter such as tar, sugar residues, etc., then pressing into moulds, and baking in a furnace, is used both for battery plates and for the carbon rods used in arc lamps.

the carbon of one cell to the zinc of the next. The top part of the carbon is sometimes impregnated with paraffin wax to keep the acid from creeping up, and electrotyped with copper. Fig. 103 shows the usual way of coupling up a series of five such cells. The Bunsen's battery will continue to furnish a current for a longer time than the flat Grove's cells, on account of the larger quantity of acid contained by the cylindrical pots.*

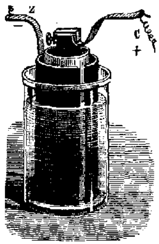


Fig. 102.

Chromic solutions, formed by adding strong sulphuric acid to solutions of bichromate of potash or of soda, are often used instead of nitric acid, in cells of this form.

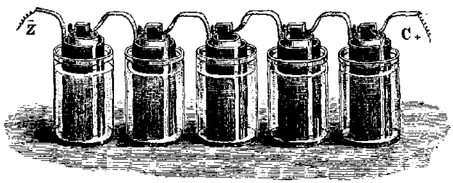


Fig. 103.

Soluble depolarizers in the form of chromic powders are made by heating strong sulphuric acid and gradually stirring into it powdered bichromate of soda. The pasty mass is then cooled and powdered.

* Callan constructed a large battery in which *cast iron* formed the positive pole, being immersed in strong nitric acid, the zincs dipping into dilute acid. The iron under these circumstances is not acted upon by the acid, but assumes a so-called "passive state." In this condition its surface appears to be impregnated with a film of magnetic peroxide, or of oxygen.

184. Leclanché's Cell.—For working electric bells and telephones, and also to a limited extent in telegraphy, a zinc-carbon cell is employed, invented by Leclanché, in which the exciting liquid is not dilute acid, but a solution of salammoniac. In this the zinc dissolves, forming a double chloride of zinc and ammonia, while ammonia gas and hydrogen are liberated at the carbon pole. The depolarizer is the black binoxide of manganese, fragments of which, mixed with powdered carbon, are held up to the carbon kathode either by packing them together inside a porous pot or by being attached as an agglomerated block. The oxide of manganese will slowly yield up oxygen as

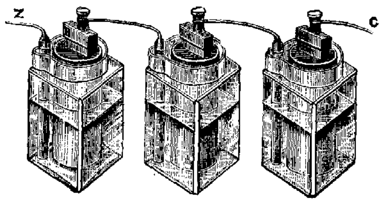


Fig. 104.

required. If used to give a continuous current for many minutes together, the power of this cell falls off owing to the accumulation of the hydrogen bubbles ; but if left to itself for a time the cell recovers itself, the binoxide gradually destroying the polarization. As the cell is in other respects perfectly constant, and does not require renewing for months or years, it is well adapted for domestic purposes. It has the advantage of not containing corrosive acids. Millions of these cells are in use on "open-circuit" service—that is to say, for those cases in which the current is only required for a few moments at a time, and the circuit usually left open. Three

Leclanché cells are shown joined in series, in Fig. 104. Walker used sulphur in place of oxide of manganese. Niaudet employed bleaching powder (so-called chloride of lime) as depolarizer, it being rich in chlorine and oxygen. Common salt may be used instead of salammoniac.

Modifications of the Leclanché cell in which the excitant cannot be spilled are used for portability. The space inside the cell is filled up with a spongy or gelatinous mass, or even with plaster of Paris, in the pores of which the salammoniac solution remains. They are known as *dry cells.*

185. Lalande's Cell.—This cell belongs to Class II., having as depolarizer oxide of copper mechanically attached to a kathode of copper or iron. The anode is zinc, and the exciting liquid is a 30 per cent solution of caustic potash into which the zinc dissolves (forming zincate of potash), whilst metallic copper is reduced in a granular state at the kathode. It has only 0·8 to 0·9 volts of E.M.F., but is capable of yielding a large and constant current.

186. De la Rue's Battery.—De la Rue constructed a constant cell belonging to Class III., in which zinc and silver are the two metals, the zinc being immersed in chloride of zinc, and the silver embedded in a stick of fused chloride of silver. As the zinc dissolves away, metallic silver is deposited upon the kathode, just as the copper is in the Daniell's cell. De la Rue constructed an enormous battery of over 11,000 little cells. The difference of potential between the first zinc and last silver of this battery was over 11,000 volts, yet even so no spark would jump from the + to the − pole until they were brought to within less than a quarter of an inch of one another. With 8040 cells the length of spark was only 0·08 of an inch, or 0·2 cm.

187. Gravity Cells.—Instead of employing a porous cell to keep the two liquids separate, it is possible, where one of the liquids is heavier than the other, to arrange

that the heavier liquid shall form a stratum at the bottom of the cell, the lighter floating upon it. Such arrangements are called *gravity cells*; but the separation is never perfect, the heavy liquid slowly diffusing upwards. Daniell's cells arranged as gravity cells have been contrived by Meidinger, Minotto, Callaud, and Lord Kelvin. In Siemens' modification paper-pulp is used to separate the two liquids. The "Sawdust Battery" of Kelvin is a Daniell's battery, having the cells filled with sawdust, to prevent spilling and make them portable.

188. Clark's Standard Cell.—A standard cell whose E.M.F. is even more constant than that of the Daniell was suggested by Latimer Clark. This cell, which is now adopted as the international standard cell, consists of an anode of pure zinc in a concentrated solution of zinc-sulphate, whilst the kathode is of pure mercury in contact with a paste of mercurous sulphate. Precise instructions for setting up Clark cells are given in Appendix B at the end of this book. Fig. 105 shows, *in actual size*, the form of the Clark cell. Its E.M.F. is 1·434 volts at 15° C.

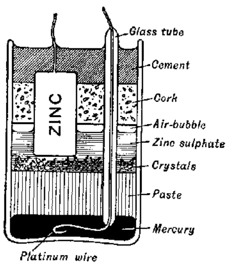


Fig. 105.

Weston uses a cadmium anode immersed in sulphate of cadmium and finds the cell so modified to give 1·025 volts at all ordinary temperatures.

Von Helmholtz has used mercurous chloride (calomel) and chloride of zinc, in place of sulphates, in a standard cell. Carhart finds its E.M.F. (a little over 1 volt) to vary with the dilution of the chloride of zinc.

189. Statistics of Cells.—The following table gives the electromotive-forces of the various batteries enumerated :—

Name.	Anode.	Excitant.	Depolarizer.	Kathode.	Approximate Volts.
Class I.		(Solution of)			
Volta (Wollaston, etc.).	Zinc	H_2SO_4	none	Copper	1·0 to 0·5
Smee . . .	Zinc	H_2SO_4	none	Platinized Silver	1·0 to 0·5
Law . . .	Zinc	H_2SO_4	none	Carbon	1·0 to 0·5
Class II.					
Poggendorff (Grenet, Fuller, etc.).	Zinc	H_2SO_4	$K_2Cr_2O_7$	Carbon	2·1
Grove . . .	Zinc	H_2SO_4	HNO_3	Platinum	1·9
Bunsen . . .	Zinc	H_2SO_4	HNO_3	Carbon	1·9
Leclanché . .	Zinc	NH_4Cl	MnO_2	Carbon	1·4
Lalande . . .	Zinc	KHO	CuO	Carbon	0·8
Upward . . .	Zinc	$ZnCl_2$	Cl	Carbon	2·0
Fitch . . .	Zinc	NH_4Cl	$KClO_3+NaClO_3$	Carbon	1·1
Papst . . .	Iron	Fe_2Cl_6	Fe_2Cl_6	Carbon	0·4
Obach (dry) . .	Zinc	NH_4Cl in $CaSO_4$	MnO_2	Carbon	1·46
Class III.					
Daniell (Meidinger, Minotto, etc.).	Zinc	$ZnSO_4$	$CuSO_4$	Copper	1·07
De la Rue . .	Zinc	$ZnCl_2$	$AgCl$	Silver	1·42
Marié Davy . .	Zinc	$ZnSO_4$	Hg_2SO_4	Carbon	1·4
Clark (Standard) .	Zinc	$ZnSO_4$	Hg_2SO_4	Mercury	1·434
Weston . . .	Cadmium	$CdSO_4$	Hg_2SO_4	Mercury	1·025
Von Helmholtz .	Zinc	$ZnCl_2$	Hg_2Cl_2	Mercury	1·0
Class IV.					
Accumulators. (Planté, Faure, etc.)	Lead	H_2SO_2	PbO_2	Lead	2·1 to 1·85

190. Strength of Current.—The student must not mistake the figures given in the above table for the strength of current which the various batteries will yield ; the current depends, as was said in Lesson XIII., on the internal *resistance* of the cells and on that of their

circuit, as well as on their E.M.F. The E.M.F. of a cell is independent of its size, and is determined solely by the materials chosen and their condition. The resistance depends on the size of the cell, the conducting qualities of the liquid, the thickness of the liquid which the current must traverse, etc.

The definition of the **strength** of a current is as follows: *The strength of a current is the quantity of electricity which flows past any point of the circuit in one second.** Suppose that at the end of 10 seconds 25 *coulombs* of electricity have passed through a circuit, then the average current during that time has been $2\frac{1}{2}$ *coulombs per second*, or $2\frac{1}{2}$ *amperes.* The usual strength of currents used in telegraphing over main lines is only from five to ten thousandths of an *ampere.*

If in t seconds a quantity of electricity Q has flowed through the circuit, then the current C during that time is represented by the equation

$$C = \frac{Q}{t}.$$

This should be compared with Art. 162.

The laws which determine the strength or quantity of a current in a circuit were first enunciated by Dr. G. S. Ohm, who stated them in the following law:—

191. Ohm's Law.—*The current varies directly as the electromotive-force, and inversely as the resistance of the circuit;* or, in other words, anything that makes the

* The terms "strength of current," "intensity of current," are old-fashioned, and mean no more than "current" means—that is to say, the number of *amperes* that are flowing. The terms "strong," "great," and "intense," as applied to currents, mean precisely the same thing. Formerly, before Ohm's Law was properly understood, electricians used to talk about "quantity currents" and "intensity currents," meaning by the former term a current flowing through a circuit in which there is very *small resistance* inside the battery or out; and by the latter expression they designated a current due to a *high electromotive-force.* The terms were convenient, but should be avoided as misleading.

E.M.F. of the cell greater will increase the current, while anything that increases the resistance (either the internal resistance in the cells themselves or the resistance of the external wires of the circuit) will diminish the current.

In symbols this becomes

$$\frac{E}{R} = C,$$

where E is the number of *volts*, R the number of *ohms* of the circuit, and C the number of *amperes* of current.

> *Example.*—To find the current that can be sent through a resistance of 5 *ohms* by an E.M.F. of 20 *volts*. $20 \div 5 = 4$ *amperes*.

(See further concerning Ohm's Law in Lesson XXXIII.) Ohm's Law says nothing about the energy or power conveyed by a current. The *power* of a current is proportional both to the current and to the electromotive-force which drives it (see Art. 435).

192. Resistance and Grouping of Cells.—The internal resistances of the cells we have named differ very greatly, and differ with their size. Roughly speaking, we may say that the resistance in a Daniell's cell is about five times that in a Grove's cell of equal size. The Grove's cell has indeed both a higher E.M.F. and less internal resistance. It would in fact send a current about eight times as strong as the Daniell's cell of equal size through a short stout wire.

We may then increase the strength of a battery in two ways :—

(1) By increasing its E.M.F.

(2) By diminishing its internal resistance.

The electromotive-force of a cell being determined by the materials of which it is made, the only way to increase the total E.M.F. of a battery of given materials is to increase the number of cells joined "in series." It is

frequent in the telegraph service to link thus together two or three hundred of the flat Daniell's cells; and they are usually made up in trough-like boxes, containing a series of 10 cells, as shown in Fig. 106.

To diminish the internal resistance of a cell the following expedients may be resorted to:—

(1) The plates may be brought nearer together, so that the current shall not have to traverse so thick a stratum of liquid.

(2) The size of the plates may be increased, as this

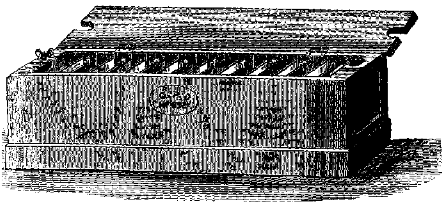


Fig. 106.

affords the current, as it were, a greater number of possible paths through the stratum of liquid.

(3) The zincs of several cells may be joined together, to form, as it were, one large zinc plate, the coppers being also joined to form one large copper plate. Suppose four similar cells thus joined "in parallel," the current has four times the available number of paths by which it can traverse the liquid from zinc to copper; hence the internal resistance of the whole will be only $\frac{1}{4}$ of that of a single cell. But the E.M.F. of them will be no greater thus than that of one cell.

It is most important for the student to remember that the current is also affected by the resistances of the wires of the *external* circuit; and if the external resistance be

already great, as in telegraphing through a long line, it is little use to diminish the internal resistance if this is already much smaller than the resistance of the line wire. It is, on the contrary, advantageous to increase the number of cells in series, though every cell adds a little to the total resistance.

Example.—If the line has a resistance of 1000 *ohms*, and five cells are used each of which has an E.M.F. of 1·1 *volt* and an internal resistance of 3 *ohms*, by Ohm's Law the current will be 5·5 ÷ 1015; or 0·0054 *ampere*. If now eight cells are used, though the total resistance is thereby increased from 1015 to 1040 *ohms*, yet the E.M.F. is increased from 5·5 to 8·8 *volts*, and the current to 0·0085 *ampere*.

The E.M.F. of the single-fluid cells of Volta and Smee is marked in the table as doubtful, for the opposing E.M.F. of polarization sets in almost before the true E.M.F. of the cell can be measured. The different values assigned to other cells are accounted for by the different degrees of concentration of the liquids. Thus in the Daniell's cells used in telegraphy, *water* only is supplied at first in the cells containing the zincs; and the E.M.F. of these is less than if acid or sulphate of zinc were added to the water.

193. Other Batteries.—Numerous other forms of battery have been suggested by different electricians. There are three, of theoretical interest only, in which, instead of using two metals in one liquid which attacks them unequally, two liquids are used having unequal chemical action on the metal. In these there is no contact of dissimilar metals. The first of these was invented by the Emperor Napoleon III. Both plates were of copper dipping respectively into solutions of dilute sulphuric acid and of cyanide of potassium, separated by a porous cell. The second of these combinations, due to Wöhler, employs plates of aluminium only, dipping respectively into strong nitric acid and a solution of caustic soda. In the third,